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The ion capturing effect of $5^\circ$ SiO$_x$ alignment films in liquid crystal devices

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We show that SiO$_x$, deposited at $5^\circ$ to the interior surface of a liquid crystal cell allows for a surprisingly substantial reduction in the ion concentration of liquid crystal devices. We have investigated this effect and found that this type of film, due to its surface morphology, captures ions from the liquid crystal material. Ion adsorption on $5^\circ$ SiO$_x$ film obeys the Langmuir isotherm. Experimental results shown allow estimation of the ion capturing capacity of these films to be more than an order of 10 000/ $\mu$m$^2$. These types of materials are useful for new types of very low power liquid crystal devices such as e-books. © 2010 American Institute of Physics.

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I. INTRODUCTION

Ions have been long known to commonly exist in liquid crystals.$^{1,2}$ Liquid crystal devices are operated by the orientational response of the average long axis of the liquid crystal molecules to an applied electric field. However, the drift of ions in these devices allows them to shield the liquid crystal material from the applied field in a time dependent and uncontrollable manner. In liquid crystal displays (LCDs), this can result in degradation of image quality by image sticking and flicker, especially if any dc voltage is applied. To overcome the ion problems, a 60 Hz signal is typically used to drive the active matrix LCDs (AMLCDs). In this case the ions are not able to accumulate at the interior surfaces of the device, and problems with them are minimized.

However, when displaying a static image, this driving scheme also consumes extrapower from the display electronics and the charging and discharging of the relatively large capacitance of the display panel. Hence, if we can lower the ion concentration in liquid crystals to the extent that the refresh rate can be changed dynamically according to the dynamic nature of displayed images, the power consumption of AMLCD can be decreased dramatically.

To address the ion problems in liquid crystals, people have done studies on charge injection, generation, and electrode interface polarization, which have proved that ions in liquid crystal displays can easily come from the commonly used polyimide alignment layers. 3,4 Also, research has been done on the dynamics of the liquid crystal director with the influence of ions, 5 adsorption currents, and the liquid crystal cell impedance affected by ions. 6,7 The dielectrical spectroscopic technique was implemented by Merck to investigate ion generation 8 and characterize the ion content in liquid crystal materials, which enables an estimation of the ion concentration and mobility. 9,10 Related to ion transport, theories, and simulation programs 11,12,13 have been developed to study the dispersive ion generation, 14 the measurement techniques for ions, 15 lateral ion transport, 16 and boundary image retention. 17

I. INTRODUCTION

In terms of low refresh rate LCDs. A driving concept has been presented to lower the power consumption for low frequency-driven light shutters. 18 Also, a memory unit was introduced in an AMLCD to store the digital signal, and thus lower the refresh rate. 19,20 A polarizer-free Reflective LCD prototype was presented, 21 driven at low frequency driving (less than 1 Hz). However, none of these prior efforts have allowed for a low refresh rate AMLCD device with gray scale because they use methods to attempt to overcome the effect of ions that only works in certain applications. To obtain the desired device, the concentration of ions must be reduced.

In a recent paper, 22 we reported the observation that the undesirable effects of ions are substantially reduced by the substitution of a typical alignment layer used in LCDs, that is polyimide based, with a less typical inorganic alignment layer consisting of an obliquely evaporated layer of SiO$_x$. In that work we found that the degree of the reduction in the effect of ions was surprising and greater than anticipated.

In this paper we provide insight into the nature of this unexpected result. A main point of this paper is to verify that the lowering of the ion concentration was due to more than the lower amount of ions introduced, and also to determine if the effect is more related to the specific inorganic material used, or to its surface morphology.

II. SiO$_x$ ALIGNMENT

The alignment method we study is SiO$_x$ deposition technique, which was invented by Janning in 1970s. 23 With this technique, one is able to induce a wide range of pretilt angle which is extremely difficult to produce on traditional polyimide alignment layers. Besides, the SiO$_x$ deposition process is clean. Compared to rubbed polyimide, SiO$_x$ deposition does not generate so many ions that contaminate the alignment surface. Also, being an inorganic material, unlike polyimide, SiO$_x$ alignment layers would not serve as an ion source in liquid crystal cells.

When implementing SiO$_x$ deposition, the deposition angle of the incoming material to the surface of the target substrate has a large effect on the pretilt angle which the
liquid crystal director will acquire. This has been studied previously, \(^{24}\) which shows that obliquely evaporated films provide two distinct types of alignment for evaporation angles that are closed to 5° and 30°. Other angles give less distinct and reproducible alignment effects for liquid crystal. Therefore, in this paper, our focus is on 5° and 30° deposition. For 5° alignment, the high pretilt angles are induced dependent on the film thickness. The alignment direction is pointing to the deposition source, in the plane formed by the deposition direction and the normal of the substrate. On the other hand, 30° film induces a pretilt as small as 0°, and its alignment direction is perpendicular to the plane formed by the deposition direction and the normal of the substrate. Our observation is consistent with Ref. \(^{24}\). Further it has been shown that the surface morphologies generated by these two deposition angles are quite different. \(^{25}\) 5° deposition yields a highly porous surface, shown in Fig. 1, while 30° deposition results in a more compact structure and a smooth surface. \(^{25}\)

From Fig. 1, we can see the surface structure is highly porous which is consistent with the simulation made by a group in University of Alberta. \(^{26}\) The surface area of 5° film is much larger than that of 30° film. With a larger surface area, it is possible that it has the ability to adsorb more ions from the liquid crystal material, compared to a 30° film. This is one of the questions that are addressed in this paper.

III. EXPERIMENT AND DATA

To coat SiO\(_x\) alignment film, we use SiO\(_x\) deposition equipment from Kurt J. Lesker Co. SiO\(_x\) materials were from CERAC Inc. The SiO\(_x\) deposition took place in a high vacuum bell jar at room temperature. The SiO\(_x\) boat, placed at 70 cm from the substrate, was a multiheat-baffled, tantalum boat made by the R.D. Mathis Co. The amount of silicon oxide evaporated during the deposition was monitored by an Inficon XTM/2 deposition monitor using a sensor-crystal (Gold, 6 MHz, 0.550 in. diameter, Maxtek, Inc.). The incident angle of the beam is set at 5° or 30° (with respect to the substrate). The depositions were done at 10\(^{-5}\) – 10\(^{-6}\) torr, and the SiO\(_x\) was evaporated to the substrate at a rate about 3–5 Å/s. After getting the desired SiO\(_x\) film thickness, we assembled the substrates as electrical controlled birefringence (ECB) cells with the cell gap within 5–6 µm by UV cured glue, Norland 68. Finally, the liquid crystal ZLI4792 was vacuum-filled into the cells.

A. Comparison between 5° cells and 30° cells

The first experiment we did was to compare the ion concentration between 5° cells and 30° cells with different SiO\(_x\) film thicknesses. Two groups of cells were made with different deposition angles, 5° and 30°, respectively. Within each group, different film thicknesses were coated to study the film thickness dependence of ion concentration. The film thickness was monitored by Inficon XTM/2. Since the detection crystal was placed perpendicular to the line between it and the SiO\(_x\) source boat, while the glass substrates were mounted obliquely to the SiO\(_x\) source boat, the thickness detected by the crystal was different from that deposited on the substrates. We can use the following equation to estimate the thicknesses on the substrates: \(^{27}\)

\[
d_s = D \sin(\theta),
\]

where \(D\) is the thickness detected by the crystal, \(\theta\) is the deposition angle (5° or 30°), and \(d_s\) is the thickness of SiO\(_x\) on the glass substrates.

To characterize the ion concentration in liquid crystal, voltage holding ratio (VHR) is used, which is a standard criteria to evaluate AMLCDs in industry. The pixels in AMLCDs are charged with a short voltage pulse, and then prefer to hold the charge over a longer time period after the pixel is disconnected from the voltage source. However, owning to the existence of mobile ions, the voltage experienced by the liquid crystal material decreases with time, instead of being constant at the applied voltage. VHRs were measured with 2 V pulses at 1 Hz which can magnify the effect of ion migration. A 50 µs switching pulse is generated by a complementary metal-oxide-semiconductor (CMOS) analog switch, MAX327CPE. This device is in a high impedance state for the remainder of the measurement period. The voltage on the cell is detected by a model AD549 preamplifier. We checked the measurement system by measuring the VHR for an empty cell which showed a VHR of 0.99. Our VHR is defined via the following equation:

\[
VHR = \frac{V_{end}}{V_{peak}},
\]

where \(V_{peak}\) is the voltage at the beginning of half cycle and \(V_{end}\) represents the voltage before the polarity is switched. In this way, the larger VHR means lower ion concentration. The VHR versus film thickness curves are depicted in Fig. 2 for both 5° cells and 30° cells.
From the Fig. 2, we can see the VHRs of 5° cells keep at a level close to 1, which means low ion concentrations in 5° cells. On the other hand, the VHRs of 30° cells increase with the SiO_x film thicknesses but still smaller than those of 5° cells. So it appears that there are more ions in 30° cells than in 5° cells.

B. Double-patch cell

To explain why 5° cells have fewer ions than 30° cells, we postulate that the highly porous surface of 5° SiO_x films makes them more capable to adsorb ions than 30° films, so fewer mobile ions exist in 5° cells. To check whether this assumption makes sense, double-patch cells, depicted in Fig. 3, were designed.

In the figure, there are two areas of SiO_x layers on one substrate. The pattern is formed by the shadow mask during the deposition. Half of the substrate is covered by 5° film, while the rest is covered with 30° film. The areas of 5° and 30° are almost identical, about 1 cm^2. The thicknesses of 5° and 30° film are controlled to be the same thickness around 100 Å. Three batches of double-patch cell were made. Each batch consists of two cells, one of which was filled from 5° to 30° area, while the other was filled in the opposite direction. We compare the VHRs of 30° patch within the same batch, shown in Table I.

From the table, we can see the VHRs at 5° areas are all good, almost close to 1, which is consistent with the results in the first experiment for 5° SiO_x cells. On the other hand, at 30° areas, it is interesting that the VHRs within each patch show a big difference for different filling directions. When the liquid crystal is filled from 30° to 5° areas, the VHRs are within the same range as those in the first experiment. However, with the liquid crystal filled in the opposite direction, the VHRs at 30° areas are improved pronouncedly. Therefore, the filling direction plays an important role in determining the ion concentrations at 30° areas, which we ascribe to the ion adsorption of 5° SiO_x film.

C. LONG cell

Since the experiment on double-patch cells shows that the ion adsorption of 5° SiO_x film possibly improve the VHRs for 30° cells in double-patch cells, and also makes 5° cells have better VHRs, we conducted an experiment on the cell with multiple stripes of 30° and 5° films to quantify the ion adsorption of the 5° films. The pattern was also obtained by the shadow mask. We call this cell LONG cell, illustrated in Fig. 4.

In the figure, the light areas are 5° films without electrode pattern, while the dark patches represent the 30° films which cover the 1 x 1 cm^2 indium tin oxide (ITO) electrodes. The 30° areas are labeled by patches 1–6. The liquid crystal was filled from patch 1 to patch 6. The width of each 5° patch is about 2 mm, and they are almost identical to each other. Therefore, given the assumption of ion adsorption, it is expected that the number of mobile ions in liquid crystal will decrease with the 5° area that the liquid crystal traversed. In the filling process, the liquid crystal first enters patch 1. For the sake of convenience, the first volume of injected liquid crystal occupying patch 1 is called first VOL (volume of liquid crystal), while the second volume is second VOL, and so on. We chase each individual VOL during the filling process, and observe how its mobile ion concentration changes subject to the adsorption of 5° film. For example, when we fill the LONG cell, first VOL first passes over patch 1 and then reaches patch 2; because of ion adsorption of the 5° film between patch 1 and 2, its mobile ion concentration decreases. The difference in the number of ions represents the ions adsorbed by the 5° film. Therefore, we have an ion adsorption corresponding to an ion concentration. Based on this idea, if we can measure the ion concentration during filling, the relation between ion adsorption and ion concentration can be derived.

To calculate the amount of mobile ions, instead of VHR method, we need to implement the current-bump technique which is based on the method proposed by Ref. 15. Though VHR can offer an intuitive idea about which cell has more ions, we cannot derive the number of ions precisely with this method. Since VHR measurement works at the constant

### Table I. VHRs for the double-patch cells which consist of 5° SiO_x area and 30° SiO_x area.

<table>
<thead>
<tr>
<th>Patch</th>
<th>Batch 1(VHR)</th>
<th>Batch 2(VHR)</th>
<th>Batch 3(VHR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5° area</td>
<td>30° area</td>
<td>5° area</td>
</tr>
<tr>
<td>From 5° to 30°</td>
<td>0.92</td>
<td>0.66</td>
<td>0.93</td>
</tr>
<tr>
<td>From 30° to 5°</td>
<td>0.89</td>
<td>0.33</td>
<td>0.93</td>
</tr>
</tbody>
</table>
charge mode, the voltage decay represent the ions that shield the charges on the electrodes. However, if the number of mobile ions is so large that a portion of ions can totally compensate the charges on the electrodes, the remaining mobile ions which are not separated cannot be reflected by the voltage decay. So it is not accurate to use VHR to estimate the ion number. On the other hand, in current-bump technique, the test cells are driven with squarewave which keeps the cell at a constant voltage, so all mobile ions in liquid crystal can be driven by the applied field and generate an electric current. This mobile ion current will add an additional current bump to the discharge current after the switch of polarity in the squarewave. Since the current generated by ions is small, in the order of nanoa, a transimpedance amplifier is used to enlarge the signal and suppress the noise. The setup is shown in Fig. 5. In the figure, the amplifier tends to keep the potentials of both inputs at the same level. Therefore, the output potential is given

$$V_{\text{out}} = IR_{22},$$

where \( I \) is the current through the liquid crystal cell and \( R_{22} \) is the resistor. The current we measure is in the order of nanoampere, so we have \( R_{22} \) with the resistance of 1 MΩ so that the output voltage can be measured in the order of millivolt. S2 is connected to an oscilloscope, which measures the current profiles. A typical current profile is shown in Fig. 6.

The figure depicts a current profile of liquid crystal cell under an ac squarewave which is 4 V at 7 Hz in our measurement giving us the best signal-to-noise ratio. We can see the current peak appears about \( t_{\text{peak}} \) 10 ms after the polarity switched, \( t_{\text{peak}} \) is not the same as the ion transient time, \( t_{\text{tran}} \), given by28,29

$$t_{\text{tran}} = \frac{t_{\text{peak}}}{0.8} = 13 \text{ ms},$$

which means ions need to take 13 ms to migrate through the cell. The current bump in the profile is induced by the mobile ions in liquid crystal. Therefore, the number of ions in liquid crystal can be obtained by the following equation:15

$$N = \frac{1}{e} \int_{t_0}^{t_{\text{end}}} idt,$$

where \( e = 1.6 \times 10^{-19} \text{ C} \). \( t_{\text{end}} - t_0 = 68 \text{ ms} \), which is about five times of the ion transient time, so all the mobile ions should be included within this integral range. However, we can see the current at \( t_{\text{end}} \) does not decay completely to zero, and ends up with a quasisteady current. Such quasisteady current can be attributed to the injection of ions from electrode, surface current, extremely slow ions, and dissociation of neutral impurities, which are not the conventional mobile ions.30 Normally, the ions people talk about in liquid crystal are the mobile ions inducing the transient current. In this paper, we are also focused on the intrinsic mobile ions. Therefore, the integral given by Eq. (5) includes the transient current induced by the mobile ions, and should provide a reasonable estimate on the mobile ion concentration in liquid crystal.

In the experiment on the LONG cell, current measurement was taken during filling process. Every time when the front of first VOL reaches the boundary between 30° patches, the current profiles were measured for the 30° patches which have been occupied by liquid crystal. For example, when first VOL finished filling first 30° patch, we took the current measurement on first patch and knew its ion density. Then when the first VOL reached the boundary between second and third patch, the current measurement was taken for second patch, with which we can calculate the ion density of first VOL in second patch. The same measurement can be applied on second VOL. With the electric current data, we can implement Eq. (5) to calculate the number of ions, \( N \), in the liquid crystal at a 30° patch. The difference of ions number between the adjacent 30° patch for a VOL represents the amount of ions adsorbed by the 5° film in between. Then, the relation between ions adsorption and ion number can be derived. It took about 60 s for first VOL to progress over a 30° patch, so the time interval between each current measurement is about 1 min. Since first VOL traverses five stripes of 5° SiO films, while second VOL traverses four stripes of 5° SiO films, and so forth, in the measurement, we focus on first VOL and second VOL which have enough data points for fitting. Figure 7 shows the relation between ion adsorption and ion concentration for first VOL and second VOL, where ion concentration is given by

$$C = \frac{N}{dS_e},$$

\( \frac{d}{S_e} \) is the cell thickness and \( S_e \) is the electrode area; ion adsorption per unit area is obtained by
In Sec. III A, we compare the VHRs between 5° cells and 30° cells. It is shown that the 5° cells have fewer ions than 30° cells. Since in both kinds of cells, the alignment material is SiOx, the fewer ions in 5° cells are not due to the alignment material. To explain this, a possible reason for the superiority of 5° film could be the surface morphology. As mentioned above, 5° films have a highly porous surface, while 30° deposition forms a grooved structure. Therefore, it is possible that with a large surface area, 5° films are able to capture much more ions in liquid crystal than 30° films and therefore, the VHRs of 5° cells are larger than 30° cells.

To test the assumption of ion adsorption, we conducted the experiment on the double-patch cells. The results show that the VHRs at the 30° areas depend on the filling direction. The VHRs at the 30° areas can be improved noticeably when the liquid crystal is filled from 5° to 30° area. Based on our postulate of ion adsorption, this result can be explained. When we fill the liquid crystal from the side of 5° film, it is expected that 5° film will adsorb the ions in liquid crystal, and thus the ions become fewer when the liquid crystal reaches the area of 30° film, which helps to improve VHRs in 30° film. When filled in the opposite direction, the liquid crystal cannot be purified by the 5° film, so low VHRs were observed at the 30° areas. These results meet our postulate that 5° SiOx films have stronger ion adsorption ability.

Based on this, the experiment on LONG cell was taken to further understand and quantify the ion adsorption of 5° SiOx film. According to Ref. 31, ions adsorbed can be released from the alignment layer. The desorption time constants given by Ref. 31 are 90 and 2400 s, which are larger than the time interval between each current measurement taken in our experiment. Therefore, the desorption of ions did not significantly influence ion density estimated by the present method. Further, another simple experiment was done to ensure that the ion desorption will not affect our ion density measurement. The test cell was designed based on the idea of LONG cells, and called simplified LONG cell, shown in Fig. 8, where there is a strip of 5° film between two 30° patches, so the VHR of patch 2 will be larger than that of patch 1 due to ion adsorption of 5° film. If liquid crystal is filled from patch 1 to patch 2. In the experiment, the VHRs for both patches were measured first. Then the test cells were heated to 80 °C, and stayed at 80 °C for 20 min. It was expected that ions would have enough time and energy to escape from 5° film and uniformly diffuse through the whole cells. The VHRs were not measured at 80 °C because the cell thickness will change due to thermal expansion which will affect the VHR measurement. What we did is to cool the test cell back to room temperature in 5 min, measure the VHRs again and compare them with the initial values. If the ions adsorbed can escape from the 5° film, we expected that the VHRs of batch 1 and batch 2 will become similar to each other, after 20 min aging at 80 °C. The results of experiment are shown in Table II. We can see that because of the ion adsorption of 5° film, the initial VHR of patch 2 is much larger than that of patch 1. After 20 min aging at 80 °C, the VHRs of patch 1 and 2 were measured and compared with the initial values, showing that the VHRs did not change significantly. This result means that the trapping of ions on 5° SiOx film is strong, and most ions adsorbed on the alignment layer cannot escape even at 80 °C for 20 min. Therefore, ion desorption will not affect our current measurement to estimate the ion densities.

The experiment results of LONG cell are show in Fig. 7. We can see for both first VOL and second VOL, the ion adsorption increases with the ion concentration, which means the more ions a 5° SiOx film sees, the more ions it adsorbs. With more ions around, the adsorption sites on the 5° SiOx film have bigger probability to capture the ions from

![Graph](image.png)

**FIG. 7.** (Color online) Ion adsorption vs ion concentration in the LONG cell.

\[ A = \frac{\Delta N}{S_a}, \]

\( \Delta N \) is the number difference between the adjacent 30° patch. \( S_a \) is the area of 5° SiOx film. The figure shows that ion adsorption increase with ion concentration for both first VOL and second VOL.

**IV. DISCUSSION**

<table>
<thead>
<tr>
<th>Patch</th>
<th>Initial VHR at room temperature</th>
<th>VHR at room temperature after 80 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch 1</td>
<td>0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>Patch 2</td>
<td>0.93</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**TABLE II.** VHRs of patch 1 and patch 2 of simplified LONG cell before and after 80 °C aging.
liquid crystal. Also, it can be found that the adsorption for the first VOL is larger than second VOL. This is assumed to be because when second VOL traverses the 5° SiOx films, the adsorption sites have been partially filled by the ions from first VOL. Therefore, fewer adsorption sites are available for second VOL, and the 5° SiOx films adsorb fewer ions from second VOL than first VOL when they have the same ion concentration.

To model the data in Fig. 7, we implement Langmuir isotherm which can describe the adsorption in porous materials well. The Langmuir equation is given with the modification according to our case

$$N_a = \frac{N_o a P}{1 + a P},$$

(8)

where $N_a$ is the maximum ion adsorption capacity, $a$ is the adsorption constant, $P$ is ion concentration for the adsorption, defined as $P = N_a/dS_a$ where $N_a$ is the number of ions reaching the adsorption surface, $d$ is the cell gap, and $S_a$ is the area of 5° film. Since there is no electrode at the 5° areas, ion adsorption can only take place when the thermal motion leads ions to the surface of 5° SiOx film. It is estimated in the Appendix that within the time when a VOL of liquid crystal passes a 5° film, only about 60% of total ions can contact the adsorption surface. So $N_o = 0.6N$. According the Eq. (6), the relation between $P$ and $C$ is given by

$$P = \frac{0.6C d S_a}{S_a} = \frac{0.6C S_e}{S_a} = 3C,$$

(9)

where $S_e:S_a = 5:1$. Then plugging Eq. (9) into Eq. (8), we have the equation to fit the experiment data.

$$N_a = \frac{3N_o a C}{1 + 3a C}.$$

(10)

We use Eq. (10) and adjust $N_o$ and $a$ to obtain the best fitting results with the data in Fig. 7. The fitting results are shown below.

From the Fig. 9, we can see in the experiment data ion adsorption seems linear with ion concentration. When $a = 3.3 \times 10^{-21} / m^3$, the best fitting curves were obtained by taking $N_o = 2800 / \mu m^2$ for first VOL and $N_o = 2000 / \mu m^2$ for second VOL, respectively. We can see the theoretical curves are not fitting the experiment data well. That’s because when $aP \sim 1$ or $aP \geq 1$, Eq. (10) is not linear. It can be expected that if $a > 3.3 \times 10^{-21} / m^3$, the fitting can be worse. However, if we let $a$ with smaller values, we can get nice fitting curves for first VOL with $N_o = 10 000 / \mu m^2$ and $a = 0.67 \times 10^{-21} / m^3$, and for second VOL with $N_o = 9500 / \mu m^2$ and $a = 0.6 \times 10^{-21} / m^3$. The nice fitting results can be ascribed to that when $aP \ll 1$, Eq. (10) can be approximate to a linear function which is consistent with the experiment data. Actually, with even smaller $a$, owning to $aP \ll 1$, the experiment data can still be fit well with a larger $N_o$. Providing to the fitting results, Langmuir isotherm is found to be able to model the experiment data of ion adsorption on 5° SiOx films. Also, when $a = 0.67 \times 10^{-21} / m^3$, we are able to fit the experiment data with $N_o = 10 000 / \mu m^2$, which means the maximum ion adsorption capacity is larger than 10 000 / $\mu m^2$.

To test this statement, we use a simple model to estimate the maximum ion adsorption capacity of 5° SiOx film. Here, we assume the adsorption surface is flat, the adsorption layer is a monolayer, and the ions adsorbed are of the same polarity. Also, at the distance which the electric energy of a pair of ions becomes comparable to $kT$, the ions cannot get any closer, and this distance will determine the adsorption capacity. To estimate this distance, we solve the following equation for $r$

$$\frac{Q^2}{4 \pi \epsilon_o \epsilon r} = kT,$$

(11)

where $Q$ is the charge, $1.6 \times 10^{-19}$ C, $\epsilon_o$ is the dielectric permittivity, and $\epsilon$ is the dielectric constant of the SiOx film, 5.5. $r$ is the distance separating ions, $k$ is the Boltzmann constant, and $T$ is the room temperature, about 300. According to the above equation, $r$ is estimate about $10^{-8}$ m. An ion adsorbed will occupy an area of $r^2$, $10^{-16}$ m$^2$. Therefore, an area of 1 $\mu m^2$ or $10^{-12}$ m$^2$ is able to adsorb the amount of ions which is given below

$$C = \frac{1}{\text{The area an ion occupy}} = \frac{10^{-12}}{10^{-16}} = 10^4.$$

(12)

We can see the maximum ion adsorption per micron square is of the order, 10 000 / $\mu m^2$. Given the fact that the surface
of 5° SiOx film is highly porous, the actual ion adsorption per micron square should be larger than 10 000/μm², which is consistent with the conclusion we obtain from the fitting parameters. To summarize, it is found that the ions adsorption behavior of 5° SiOx follows the Langmuir isotherm. Also, according to the fitting results and theoretical estimate, the maximum ion adsorption capacity of 5° SiOx should be larger than 10 000/μm².

V. CONCLUSION

We found that 5° SiOx film with larger surface area have stronger ability to adsorb ions than 30° SiOx film. The comparison between 5° and 30° SiOx cells shows that 5° SiOx cells have fewer ions, though the alignment material is the same. Further, the experiment on double-patch cells shows that 5° SiOx film is able to adsorb more ions than 30° film. The behavior of ion adsorption by 5° SiOx film was studied by the measurement of LONG cells, which shows Langmuir isotherm is applicable to ions adsorption by 5° SiOx film. Also, the fitting parameters show that the ion adsorption capacity of 5° SiOx film should be more than 10 000/μm², which is consistent with the estimate from a simple theoretical model. With ion adsorption of 5° SiOx film, we can lower the ion concentration in liquid crystal display, and driving the display with a low refresh rate becomes possible. Therefore, 5° SiOx alignment will be promising for the future low power displays driven at a low fresh rate.

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APPENDIX

When liquid crystal traverses a 5° SiOx film, ions in liquid crystal will be adsorbed by the 5° SiOx film. However, only those which reach the surface can be adsorbed. To estimate how many ions can reach the surface, we built a simple one-dimensional (1D) model illustrated in Fig. 10.

The charge number per ion is assumed to be 1. Within the cell, ions are doing 1D thermal motion without mutual interaction, which can be model the diffusion model, which is

\[
P_d = \sqrt{\frac{1}{4\pi D t}} \exp\left(-\frac{y^2}{4D t}\right).
\]  \hspace{1cm} (A1)

The equation describes a particle doing thermal motion. \(P_d\) is the probability distribution function, \(D\) is the diffusion constant of the particle, \(t\) is the time of diffusion, and \(y\) is the location of the particle. In experiment, it took about 1 s for the liquid crystal of the same area of 5° SiOx film to traverse the 5° SiOx film. Therefore, to implement this model, the only parameter we need to know is the diffusion constant of ions in our liquid crystal, which can be derived from the current bump measurement. In current-bump measurement, we found the current bumps almost appear at the same time for different cells. All the peaks induced by ion migration are located within the range of 10 ms. It is safe to say all the cells have the same type of ions impurities. It is known that \(t_p\), at which the current reach its maximum is smaller than the transit time \(t_{trans}\) which is 13 ms, given by Eq. (4)

\[
\mu = \frac{d^2}{t_{trans} V},
\]  \hspace{1cm} (A2)

where \(d\) is the cell gap and \(V\) is the applied voltage, 4 V. With the mobility, the diffusion constant is given according to Einstein relation

\[
D = \frac{k_B T}{q},
\]  \hspace{1cm} (A3)

where \(k_B\) is the Boltzmann constant, \(T=297\text{ K}\), and \(q=1.6 \times 10^{-19}\text{ C}\). \(D\) is calculated to be \(1.23 \times 10^{-11}\text{ m}^2\text{s}^{-1}\). We assume \(N\) is the total ions, and the initial ion distribution is uniform, so the ion density is \(N/d\). For the ions initially at the location \(x\), the amount of ions which can reach the surface is given

\[
dN = \frac{N}{d} \left[1 - \frac{1}{\sqrt{4\pi D t}} \exp\left(-\frac{y^2}{4D t}\right)\right].
\]  \hspace{1cm} (A4)

Then, integrating the above equation, we can obtain the total number ions which can contact the surface.

\[
N_{surf} = \int_0^d dN dx = 0.6N.
\]  \hspace{1cm} (A5)

Therefore, we can see about 60% of the total ions can reach the surface, and the 5° SiOx film will only adsorb these ions.


