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## Liquid Crystals

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### Investigation on ion movement in the fringe-field switching mode depending on resistivity of alignment layer and dielectric anisotropic sign of liquid crystal

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## Investigation on ion movement in the fringe-field switching mode depending on resistivity of alignment layer and dielectric anisotropic sign of liquid crystal

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Adsorption and desorption of ions at interface between liquid crystal and alignment layer in liquid crystal displays play a crucial role in residual direct current voltage associated with image sticking. In this article, the dependency of such adsorption and desorption of ions on resistivity of alignment layer and sign of liquid crystal dielectric anisotropy in the fringe-field liquid crystal cell has been investigated. Our studies show that the time constant of ions during adsorption and desorption depends upon resistivity and dielectric constant of liquid crystal and alignment layer, and most strongly influenced by the resistivity of alignment layer such that the one with lower resistivity in two orders shows much faster adsorption and desorption at the interface than that of the one with higher resistivity.

**Keywords:** fringe-field switching; residual DC; resistivity; alignment layer

### 1. Introduction

Nowadays, liquid crystal displays (LCDs) are dominating flat panel display market owing to its great improvements in image quality and product cost although the standing level of LCDs is challenged by organic light emitting diodes.[1] Many new liquid crystal (LC) modes such as multidomain vertical alignment (MVA),[2,3] in-plane switching (IPS),[4,5] and fringe-field switching (FFS)[6–14] contribute to the development of high image quality in LCDs. In general, LCDs use a LC with its resistivity higher than  $10^{13} \Omega \text{ cm}$  for a high voltage holding ratio because a signal voltage is given only for a time period of  $1/f$  where  $f$  is driving frequency of LCDs, and it is sandwiched between alignment layers with electrodes. Though the LC's resistivity is still quite high, the amount of ions is large enough to generate noticeable residual direct current (DC) voltage if the DC is applied to LC cell. In real thin-film transistor (TFT)-LCD driving, a pure alternating current (AC) cannot be applied at all grey scales. In the driving, whenever a signal voltage is applied to a pixel via TFT, there is a voltage drop in the pixel named feedthrough voltage and is expressed as  $\Delta V_p = C_{gs}\Delta V_g/[C_{gs} + C_s + C_{lc}(V)]$ , where  $C_{gs}$  is the gate-data parasitic capacitance of a TFT,  $C_s$  and  $C_{lc}$  represent the storage and LC capacitance, respectively; and  $V_g$  denotes the gate voltage.[15]  $C_{lc}$  is voltage-dependent so that  $\Delta V_p$  is not a constant

value during displaying different grey scales. Consequently the driving method in TFT-LCDs renders common voltage ( $V_{com}$ ) difference depending on grey scales and a single set of  $V_{com}$  value impossible, resulting in a net DC voltage applied to LC layer. As a result, applied DC voltage will attract ions and the accumulated ions at an interface between LC and alignment layer form residual DC voltage, which affects signal voltage applied to the LC layer, as shown in Figure 1.[16–19]

In this work, the dependence of adsorption and desorption of ions on the resistivity of alignment layer and dielectric anisotropy of LC in FFS cell under DC electric field have been investigated.

### 2. Ion absorption in the FFS mode

In the FFS mode, the pixel and common electrode exist with passivation layer with a thickness about  $0.4 \mu\text{m}$  between them.[20] With such an electrode structure, fringe-electric fields are generated, in which the non-uniform electric field will influence on the adsorption process of ions.[21] In the FFS mode, when a  $0.2 \text{ V DC}$  is applied to the device, the field intensity that LC layer near electrode surface at the edge of pixel electrode experiences can be high as  $0.5 \text{ V}/\mu\text{m}$  ( $0.2 \text{ V}/0.4 \mu\text{m}$ ); whereas it is only  $0.05 \text{ V}/\mu\text{m}$  for a vertical field-driven twisted nematic (TN) cell with a cell gap of  $4 \mu\text{m}$ . Therefore, whenever

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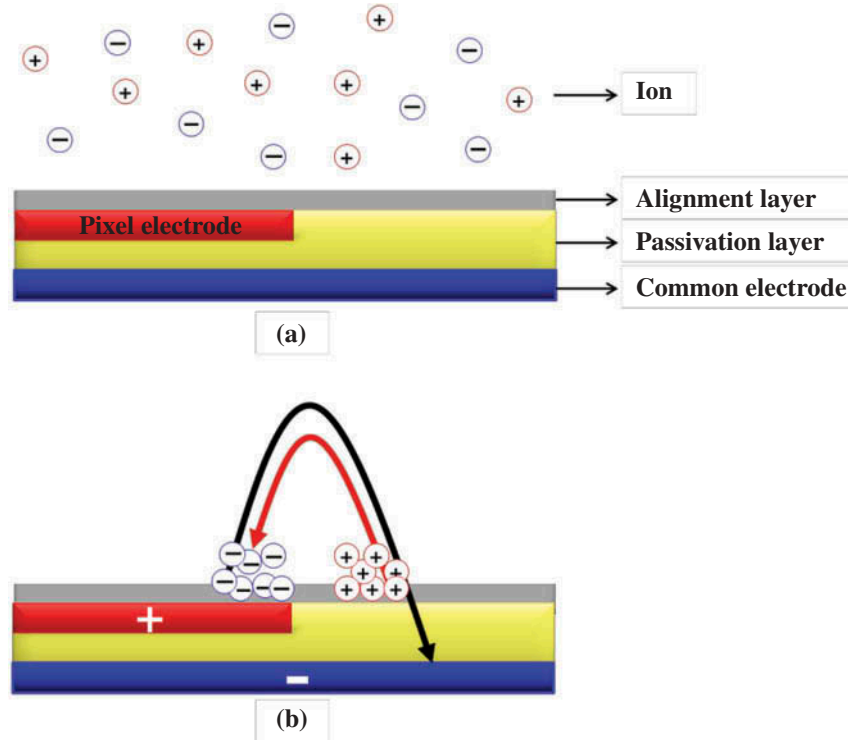


Figure 1. (colour online) (a) Cross-sectional view of FFS cell with ions in LC layer and (b) accumulated ions at an interface between LC and an alignment layer. The ions form electric field (red arrow) themselves opposite to the applied DC field (black arrow).

DC voltage exists during driving, a probability for ions to be accumulated at the interface between LC and alignment layer in the FFS device is much higher than that in a TN mode although the adsorption level of ions is expected to be electrode position-dependent due to fringe-electric field.

In the FFS cell, the electric field lines developed across the alignment and LC layers so that they would work as a load resistance between electrodes. Typically the voltage drop across any load depends upon the resistivity of the material. The voltage developed across the alignment layer causes the accumulation of ions on the surface of the electrode and gives rise to an unwanted residual DC voltage on surface of alignment layer. In view of this we investigated adsorbing and desorbing of ions depending on the resistivity ( $\rho_{AL}$ ) of an alignment layer and sign of dielectric anisotropy in the FFS cell.

### 3. Experimental

In order to understand movement of ions in the LC cell and quantify residual DC voltage formed by ions, the following experiments are performed. Two different types of LC with positive (+LC) and negative (-LC) dielectric anisotropy has been tested. The

+LC has  $\Delta\epsilon = 8.9$ , whereas -LC has  $\Delta\epsilon = -4.1$ . The specific resistivity ( $\rho_{LC}$ ) of +LC and -LC were  $1.9 \times 10^{14}$  and  $1.3 \times 10^{13}$   $\Omega$  cm, respectively. For alignment layers, two different polyimides (PIs) with resistivity of  $10^{13}$  and  $10^{15}$   $\Omega$  cm were employed. The thickness of both PIs was 1000 Å. Since residual DC voltage usually causes observable transmittance difference between positive and negative frames (known as flicker effect), the flicker is observed and minimized through changing the  $V_{com}$  offset. Finally, the amplitude of  $V_{com}$  shift is defined as the residual DC formed by ions.[22,23]

### 4. Results and discussion

In order to observe accumulation of ions, DC voltages with three different amplitudes, 0.1, 1.0 and 1.6 V are applied to the FFS cells. In the FFS cell, because of its unique electrode structure, the fringe electric field that has both horizontal and vertical field components is generated with bias voltage, and its field intensity is strongly electrode position-dependent. The horizontal field intensity that is responsible for lateral movement of ions is maximal near edge of signal electrodes and minimal at the centre of signal and common electrodes.

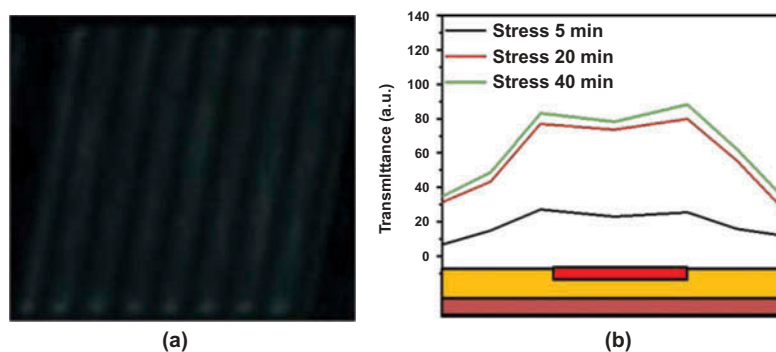


Figure 2. (colour online) (a) POM image in a dark state after DC of 1.0 V stressing for 40 min and (b) light leakages in a dark state as a function of times after applying DC of 1.0 V.

Consequently the accumulated ions should also be electrode position-dependent. We have applied a DC voltage of 1.0 V for 40 min to the cell and observed changes in transmittance as a function of time using polarized optical microscopy (POM). As clearly shown in Figure 2(a), the light leakage in a dark state is generated due to the accumulation of ions, and the level of the light leakage depends on electrode position such that the light leakage near edge of pixel electrode is the highest, indicating the level of ion accumulation is proportional to the horizontal field intensity. In addition, the light leakage increases with increasing time, indicating that the amount of accumulated ions increases as time evolves.

The amount of accumulated ions as a function of times is quantified as a residual DC by applying three different DC voltages to each cell. As shown in Figure 3(a), when a DC voltage of 0.1 V is applied, the cell with PI resistivity of  $10^{13} \Omega \text{ cm}$  (low PI) exhibits residual DC of 0.1 V after 90 min for both LCs with positive and negative dielectric anisotropy. Interestingly, when resistivity of PI is  $10^{15} \Omega \text{ cm}$  (high PI), residual DC voltage of 0.1 V is observed after 260 min, indicating clearly that the adsorbing time of ions at the interface is strongly dependent on the resistivity of PIs. Nevertheless, the maximum amplitude of residual DC is 0.1 V when the applied DC is 0.1 V. Now when the applied DC is 1.0 V, the

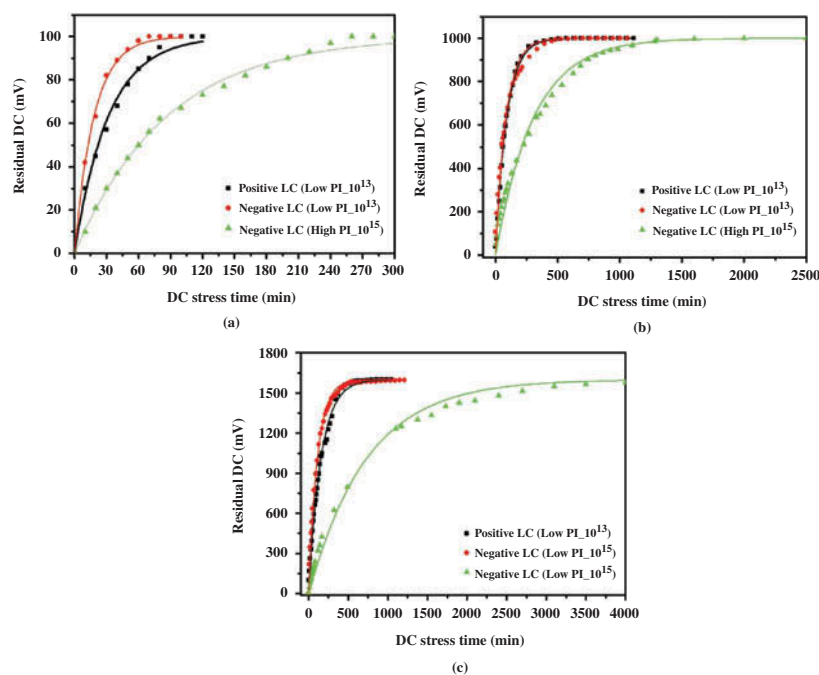


Figure 3. (colour online) Measured residual DC voltage as a function of time by applying DC voltage (a) 0.1 V, (b) 1.0 V and (c) 1.6 V. The solid lines are fitting lines with Equation (3).

maximal residual DC voltage measured was 1.0 V as shown in Figure 3(b). The adsorbing behaviour of the ions was the same in both the cases of applied DC voltages. However, the adsorbing time to reach 1.0 V takes 300 min for low PI and 1000 min for high PI. Even when a DC 1.6 V is applied, the adsorbing behaviour of ions shows similar behaviour as shown in Figure 3(c) and the only difference observed in all the three cases of applied voltages is that the adsorbing time taken by the ions to be charged to the same level of applied DC increases with increase in the applied voltage.

In order to understand the adsorbing behaviour of ions, a qualitative modelling to calculate time constant is performed. According to Mizusaki *et al.*, the desorbing (or relaxation) process of adsorbed ions (or ion density  $n_d$ ) within the open circuit after applying DC voltage for a certain period time is given as follows.[22]

$$n_d(t) = n_d(0) \exp\left(-\frac{t}{\tau_d}\right) \quad (1)$$

where  $n_d(0)$  is the density of the adsorbed ions at an initial state and  $\tau_d$  is a time constant associated with desorbing process. From Equation (1), one can expect adsorbing process of ions (or adsorbed ion density  $n_a$ ) in LC layer is given by

$$n_a(t) = n_{\text{sat}} \left[ 1 - \exp\left(-\frac{t}{\tau_a}\right) \right] \quad (2)$$

where  $n_{\text{sat}}$  is the saturated ion density of the adsorbed ions at an infinite time and  $\tau_a$  is a time constant associated with adsorbing process. Since ion density is linearly proportional to residual DC voltage, ion density can be replaced by residual DC voltage and Equation (2) can be expressed as follows:

$$V_r(t) = V_{\text{r}\infty} \left[ 1 - \exp\left(-\frac{t}{\tau_a}\right) \right] \quad (3)$$

where  $V_{\text{r}\infty}$  is a saturated residual DC voltage after an infinite time. Through fitting the experimental data using Equation (3),  $\tau_a$  can be calculated in each case. When the DC 0.1 V is applied, the calculated  $\tau_a$ s are 31.8, 18.4 and 86.6 min in +LC (low PI), -LC (low PI) and -LC (high PI), respectively. In the FFS cell, the electric field developed across the alignment and LC layers so that the  $\tau_a$  is associated with  $\rho_{\text{AL}}\epsilon_{\text{AL}}$  and  $\rho_{\text{LC}}\epsilon_{\text{LC}}$ . In first two cases, the same PI is used and the only difference is  $\rho_{\text{LC}}\epsilon_{\text{LC}}$ . Since the  $\rho_{\text{LC}}\epsilon_{\text{LC}}$  of +LC is larger than that of -LC, larger  $\tau_a$  in the +LC than in -LC can be explained. In the latter two cases, only

the  $\rho_{\text{AL}}$  of the alignment layer is different with two orders of magnitude and thus more than about four times of  $\tau_a$  in the cell with high PI than that with low PI is observed. When the DC 1.0 V is applied, the calculated  $\tau_a$ s are 90.5, 84.6 and 306.4 min in +LC (low PI), -LC (low PI) and -LC (high PI), respectively. With further higher DC 1.6 V, the calculated  $\tau_a$ s are 155.6, 110.9 and 734.8 min in +LC (low PI), -LC (low PI) and -LC (high PI), respectively. The results indicate that  $\tau_a$  takes longer with higher applied DC voltage, and one order higher  $\rho\epsilon$  in the +LC than that in the -LC causes  $\tau_a$  to be longer but less than twice and higher  $\rho\epsilon$  in two order in the high PI than that in the low PI results in  $\tau_a$  to be longer by about four times or more depending on applied DC voltage.

From the measured data and the calculated time constants for adsorption of ions, we can conclude that (i) the higher a DC is applied, the larger amount of ions can be accumulated, (ii) the adsorbing time of ions at an interface between LC and alignment layer is strongly dependent on  $\rho\epsilon$  of materials so that two-order difference in  $\rho_{\text{AL}}$  makes adsorbing time constant few times longer, (iii) the dependence of sign of dielectric anisotropy of LC on adsorbing time exists only if  $\rho\epsilon$  of LCs are different from each other; however its dependency on LC is much smaller than that of PI, and (iv) the amount of ions in LC layer is large enough to generate residual DC of 1.6 V.

The fast adsorbing time of ions implies that the image sticking can be easily observed even with small amount of DC applied and in terms of this viewpoint, a cell with use of high PI is favoured for slow appearance of image sticking. Nevertheless, the stressing time to TFT-LCD for image sticking test is quite long, in some cases about 24 hours and an expected DC voltage during driving assumes to be less than 0.5 V, then the resistivity difference in the alignment layer makes little difference.

In the LC cell, fast desorbing of accumulated ions into LC layer is also very important for fast disappearance of image sticking associated with accumulated ions. Figure 4 describes desorbing behaviour of the accumulated ions depending on materials when residual DC voltages associated with accumulated ions are 0.1 and 0.5 V. As clearly shown in all cases, the cell with low PI shows much faster desorbing than that with high PI, and the desorbing time takes longer when an amount of residual DC is large. In addition, the accumulated ions were not fully desorbed for the cell with -LC and high PI, indicating -LC that has a dipole moment at lateral parts has a disadvantage in desorption in this combination of the alignment layer tested and -LC. Overall it suggests that a cell with



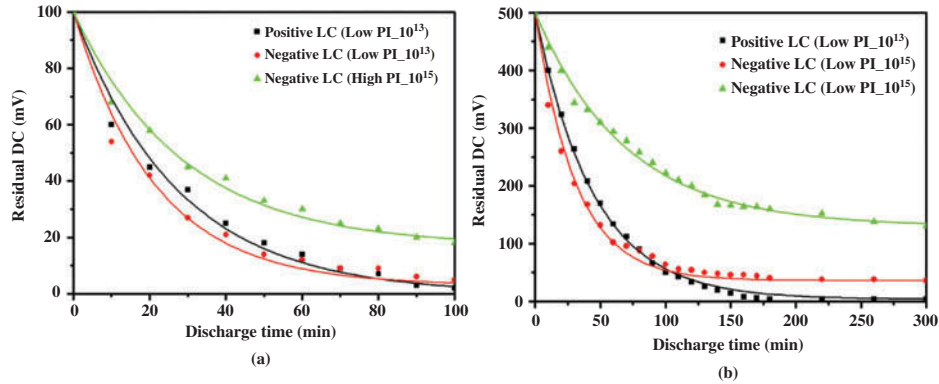


Figure 4. (colour online) Measured desorbing time of ions when a residual DC with adsorbed ions was (a) 0.1 V and (b) 0.5 V. The solid lines are fitting lines with Equation (4).

low PI is favoured for fast disappearance of image sticking.

In order to analyse the data, a desorbing time constant  $\tau_d$  is calculated using a modified Equation (1) as follows:

$$V_r(t) = V_r(0) \exp\left(-\frac{t}{\tau_d}\right) + V_{r\infty} \quad (4)$$

where  $V_r(0)$  is a residual DC voltage before starting desorption and the residual DC voltage after an infinite time  $V_{r\infty}$  is added for  $-LC$  because it is not fully desorbed after a long time. The calculated  $\tau_d$ s are 27.3, 21.4, and 28.6 min for DC 0.1 V and 44.5, 30.8, and 69.7 min for DC 0.5 V in  $+LC$  (low PI),  $-LC$  (low PI), and  $-LC$  (high PI), respectively. When a desorption starts from ions with the small DC 0.1 V,  $\tau_d$  seems to be slightly longer in a proportion to  $\rho\varepsilon$  of LC or  $\rho\varepsilon$  of PI. Unexpectedly,  $\tau_d$ s between  $+LC$  (low PI) and  $-LC$  (high PI) seem to be about the same, indicating that  $\tau_d$  is not representing desorption behaviour clearly when a residual DC is very small like 0.1 V. However, the calculated  $V_{r\infty}$ s are 0 V, 3 mV, and 17 mV in  $+LC$  (low PI),  $-LC$  (low PI) and  $-LC$  (high PI), respectively, that is, when considering desorbing process, not only  $\tau_d$  but also  $V_{r\infty}$  needs to take into account for understanding the ion relaxation process. When a desorption starts from highly accumulated ions with the DC 0.5 V, the dependency of  $\tau_d$  on  $\rho\varepsilon$  of LC and PI seems to be more pronounced such that  $\tau_d$  is longer more than two times in  $-LC$  (high PI) than in  $-LC$  (low PI) and also longer by about 1.5 times in  $+LC$  (low PI) than  $-LC$  (high PI). In this case, the calculated  $V_{r\infty}$ s are 4 mV, 36 mV, and 370 mV in  $+LC$  (low PI),  $-LC$  (low PI), and  $-LC$  (high PI), respectively, indicating that  $-LC$  with high PI is not a good combination at all for fast desorption of adsorbed ions.

## 5. Conclusion

The article investigates on accumulation of ions at an interface between LC and alignment layer, and relaxation process of the accumulated ions into LC layer. Our studies report that adsorbing and desorbing process of ions strongly depends on the product of resistivity and dielectric constant of LC layer and alignment layer that the fringe-field crosses and electrical resistivity of the alignment layer with difference in two orders mainly contributes to the ion movement, and the alignment layer with its resistivity in order of  $10^{15} \Omega \text{ cm}$  is not favoured at all for fast desorption of ions that are accumulated between LC and alignment layer. The results are important for understanding image sticking associated with ions in IPS/FFS mode.

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