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Anomalous Capacitance Bounces and Bumps of Liquid Crystal Cells in DC Electric Fields

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We have studied the time response of the capacitance of nematic liquid crystal cells by applying electric fields. When AC fields are applied, the capacitance exhibited a normal behavior: it first increased monotonically with time, and then reached a saturating value. With sufficient high DC fields, capacitance bounces and bumps were observed during the rising time for 100-μm thick cells with low and high impurity concentrations, respectively. We believe that these anomalous capacitance characteristics of liquid crystal cells are resulted from the coupling effects between induced polarization from liquid crystal molecules and space-charge polarization from fast ions.

KEYWORDS: capacitance, liquid crystal, ion, induced polarization, space-charge polarization

1. Introduction

Liquid crystal (LC) cells may contain many ions[1] which come either from the raw material itself or from impurities during the cell fabrication. The ions dissociated by an applied DC electric field move to the electrode with the opposite electric polarity and cause the ionic charge effects.

Researches on ionic charge mechanisms of LC materials usually apply the measurements of voltage,[2] current,[3] capacitance,[1,4–6] and optics.[7] Among them, the capacitance measurement gives a more effective way for analyzing the ion transportation or even the ion distribution.[1,6] The C-V characteristics in a DC electric field[4] and the time response of a LC cell in a switched DC electric field[5] were investigated to know how the DC electric fields influence the LC cells. However, there still remains some phenomena not well studied so far. In addition, the capacitance value of LC pixels (cells) directly influence the performance of a thin-film transistor liquid-crystal display (TFT-LCD) due to capacitive coupling effects[8] which produce an unexpected DC component to the LC layer. Hence, it needs much further studies on the capacitance behaviors of LC cells in DC electric fields.

In this letter, we investigated the capacitance behaviors of LC cells subjected to external electric fields. We enlarged the cell-gap for observing the transient response conveniently and added some ionic dopant into LC cells to investigate the influence of ionic charges on the capacitance behaviors. It was found that the time evolution of capacitance characteristic is different dramatically under various experimental conditions, especially when DC fields are applied. Capacitance bounces and bumps were observed in addition to the capacitance suppressions which were conventionally expected in cells driven by DC fields.[5] High impurity concentration and high applied DC voltage play crucial roles on these abnormal capacitance characteristics. These phenomena can be explained by a simple picture, which describes the coupling effects between induced polarization from LC molecules and space-charge polarization from fast ions.

2. Experiment

In our experiments, homogeneously aligned nematic LC cells with a thickness of 100 μm and an area of (2.5 cm)^2 were used. Two kinds of test cells were prepared for E7 (Merck) with and without 0.5 wt% (weight-percentage) of Tetra-n-butyl-ammonium iodide (TBAI), corresponding to a lower and a higher impurity concentration samples, cell A and cell B, respectively. The material of alignment layer (AL) was polyvinyl alcohol (PVA). The capacitance of each cell was measured at 1 kHz by a digital impedance meter (HP 4284A). The temperature of the LC cells was controlled at 24°C±1°C. Capacitance of both cells was measured to study either AC or DC field effects. We first observed AC field effects by measuring the capacitance of test cells with sinusoidal AC voltages of 3 and 12 V (rms) at 1 kHz. To study DC field effects, DC voltages of 1, 2, 3, 5, 8 and 12 V were applied and the AC voltage was reduced to 50 mV. This small AC voltage was needed for the capacitance measurement. The measured results in the DC case are shown in Fig. 1. Some of the curves in Fig. 1 with typical behaviors are replotted in Fig. 2 together with the measured results in the AC case. The capacitance in both figures is normalized by $C_\perp$ which is the capacitance of an undisturbed homogeneous cell. In our case $C_\perp = \epsilon_\perp A/d$, where A is the cell area, d is the cell-gap, and $\epsilon_\perp$ is the dielectric constant for electric field perpendicular to the LC director. Note that if the directors in LC cells all align perpendicular to

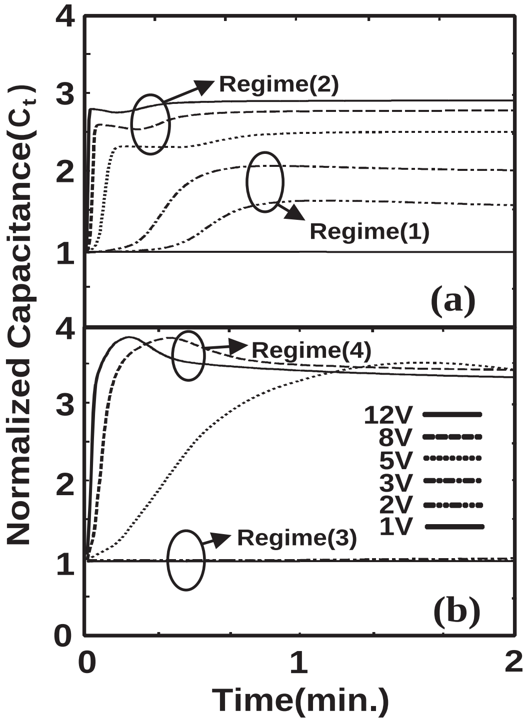


Fig. 1. Normalized capacitance as a function of time under different DC voltages for cells of (a) E7, and (b) E7 + 0.5 wt% TBAI.

the substrates, the capacitance achieves its maximum value $C_{\parallel} = \epsilon_{\parallel} A/d$, where $\epsilon_{\parallel}$ is the dielectric constant for electric field parallel to the LC director. For our cell we have $C_{\perp} = 287.8\,\text{pF}$ and $C_{\parallel} = 1051.4\,\text{pF}$.

3. Results

When only an AC voltage is applied, the LC directors respond as one would normally expect (see Fig. 2). The capacitance first increases with time after the AC voltage is switched on, and finally it reaches a saturating value. However, it behaves differently when a DC voltage is applied. In Fig. 1, four different behaviors based on applied voltages and the impurity concentration of cells can be easily seen, namely: (1) weakly smooth suppression, (2) bounce, (3) strongly smooth suppression, and (4) bumps. The results are summarized in Table I.

For regime (1) in Figs. 1(a) and 2(a), the capacitance of LC cell with small impurity concentration (cell A) and at low voltage (3 V) only suppresses weakly. For regime (3) in Figs. 1(b) and 2(c), the suppression in the cell with higher impurity concentration (cell B) becomes very strong at the same DC voltage. For regime (2) and (4), anomalous behaviors occur at a higher DC voltage (12 V). For regime (2) in Figs. 1(a) and 2(b), cell A leads to a bounce at the early time. For regime (4) in Figs. 1(b) and 2(d), the curves behave dramatically differently. They even surpass the maximum normalized capacitance $C_{\parallel}/C_{\perp}$, which is 3.65 for our cell. This capacitance bumps are obviously contributed from an extra capacitance component.

Table I. Summary of the conditions for various regimes of LC capacitance.

Impurity concentration	Electric filed Low	High
Low	(1) Weakly smooth suppress.	(2) Bounce
High	(3) Strongly smooth suppress.	(4) Bump

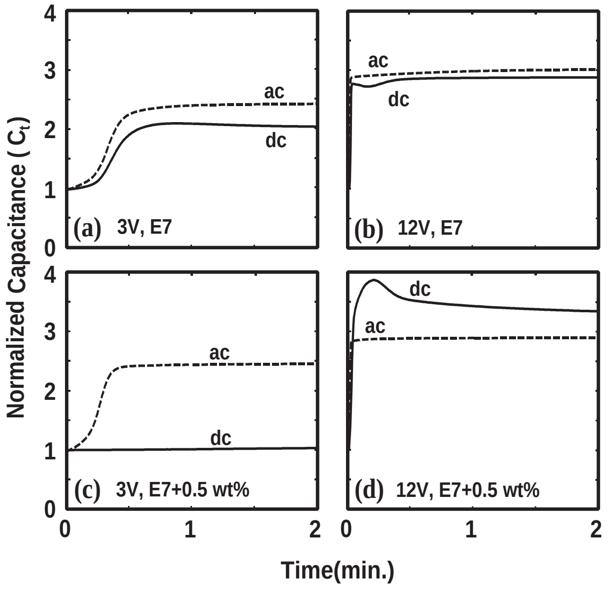
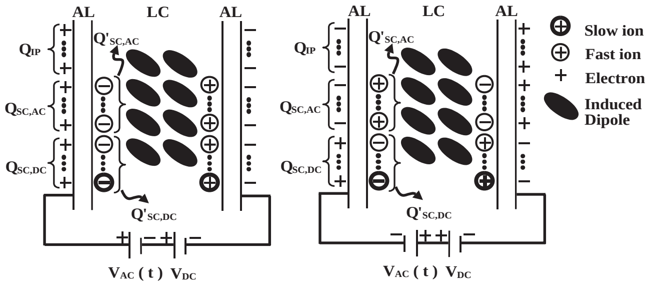


Fig. 2. Normalized capacitance as a function of time for comparison of AC and DC field effects in various regimes: (a) regime (1): weakly smooth suppression, (b) regime (2): bounce, (c) regime (3): strongly smooth suppression, and (d) regime (4): bump.

4. Discussion

Consider a LC cell with the ions dissociated by DC fields. The ions can transport in the LC layer with electric fields. The digital impedance meter with a small sinusoidal AC voltage of 50 mV at 1 kHz will read the capacitance value, C_t, composed of the induced polarization component, C_{IP}, from LC molecules and the space-charge polarization component, C_{SC}, from impurity-ions. Moreover, the total capacitance from theoretical analysis also leads to $C_t = C_{IP} + C_{SC}$,[9] which is accordant to the explanation of the anomalous capacitance behaviors in this study. Two polarization mechanisms contribute to the total capacitance behaviors of LC cells are illustrated in Fig. 3. We consider the DC driving case that both the AC field, $V_{AC}(t) = \sqrt{2}V_{ac}\sin(2\pi f t)$ (f: frequency, V_{ac}: rms value), and the DC field, V_{DC}, are applied to a LC cell. Since V_{AC} is much less than V_{DC}, it can be regarded that the LC directors are almost driven by V_{DC}. The amount of electronic charges arose with AC induced LC dipoles is Q_{IP}. Either electrons or induced LC dipoles can follow the fast alternating field ($f = 1$ kHz) and thus result in the induced polarization component C_{IP}. When V_{DC} is applied, it plays an important role on the dissociation of ions. These ions may be classified into two kinds, fast ions and slow ions, according to their mobilities. The DC field attracts an amount of its dissociated ionic charges, $Q'_{SC,DC}$, to move toward the interface of LC and AL. The $Q'_{SC,DC}$ contains both of fast and slow ions because whether the ions are fast or slow, the uni-directional electric field can offer enough time for ions to transport to the interface. These ions form an opposite field to reduce the DC field experienced by LC molecules. In other words, the LC directors experience a gradually decreasing DC voltage and then C_{IP} also decreases. However, the slow ions can not follow the high frequency (1 kHz) AC voltage in time so that the ions transport back and forth to the interfaces as the fast alternating electric field are almost fast ions. The slow ions are the native ions in E7, while the fast ions with a higher mobility of $\sim 5 \times 10^{-9}\,\text{m}^2/\text{V}\cdot\text{s}$ are analyzed to origin from TBAI.[1] The amount of fast ions contribute to C_{SC} is $Q'_{SC,AC}$. Note that $Q'_{SC,DC}$ and $Q'_{SC,AC}$ are different from the corresponding electron quantities of $Q_{SC,DC}$ and $Q_{SC,AC}$, respectively.

The effective DC voltage drives the directors dynamically



(a) (b)

Fig. 3. Illustration of the two polarization mechanisms contributing to the total capacitance of LC cells during (a) the positive polarity of $V_{AC}(t)$, and (b) the negative polarity of $V_{AC}(t)$. The amount of electrons due to induced LC dipoles, $V_{AC}(t)$, and V_{DC} are Q_{IP}, $Q_{SC,AC}$, and $Q_{SC,DC}$, respectively. Q_{IP} is related to C_{IP}. $Q_{SC,DC}$ decreases the internal electric field experienced by LC molecules and thus influences C_{IP}. $Q_{SC,AC}$ can follow the fast alternation of electric polarity in $V_{AC}(t)$ that give the component C_{SC}.

such that the capacitance $C_{\rm IP}$ should peak at some time, say $t_{\rm IP}$. It increases before $t_{\rm IP}$ and then decreases. On the other hand, the space-charge capacitance $C_{\rm SC}$ increases monotonically after the DC voltage are switched on and then it saturates. Nevertheless, it is reasonable to assume that at time $t_{\rm SC}$, $C_{\rm SC}$ reaches its maximum value. The peak capacitance that appears at $t_{\rm IP}$ and $t_{\rm SC}$ are important for the observed capacitance behaviors. Here we assume $t_{\rm SC} > t_{\rm IP}$ in view that the saturation of dissociation is slower than the response of LC directors. Another important factor is the increasing rates of $C_{\rm IP}$ and $C_{\rm SC}$ before $t_{\rm IP}$ and $t_{\rm SC}$, respectively. The increasing rates of $C_{\rm IP}$ and $C_{\rm SC}$ depend on the applied DC voltage as well as the amount of dissociated fast ions. Schematic diagrams are drawn in Fig. 4 to illustrate the relation of the behaviors of $C_{\rm IP}$ and $C_{\rm SC}$ to the resulted behavior of $C_{\rm t}$ from the above factors.

The typical curves from Fig. 1 are replotted in Fig. 4(a). Their corresponding behaviors are illustrated in Figs. 4(b), 4(c) and 4(d). The main parameters that can affect the behaviors of the capacitance are the times $t_{\rm IP}$ and $t_{\rm SC}$ and the changing rate of $C_{\rm IP}$ and $C_{\rm SC}$. Figure 4(b) represents the weekly smooth suppression for cell A (with small impurity concentration) driven by a small $V_{\rm DC}$ (3 V). The $V_{\rm DC}$ is so small that $C_{\rm SC}$ does not have distinguishable peaks in our measuring time interval. Moreover, the capacitance of cell B (with high enough impurity concentration) driven by a small $V_{\rm DC}$ (3 V) is strongly suppressed (not shown in Fig. 4). The small applied voltage is almost cancelled by that large amount of $Q'_{\rm SC,DC}$, but the dissociated fast-ions $Q'_{\rm SC,AC}$ are still not enough to give a significant $C_{\rm SC}$ component. Therefore, $C_{\rm t}$ is strongly suppression due to the small $C_{\rm IP}$ and $C_{\rm SC}$. We call this behavior strongly smooth suppression. Fig. 4(c) shows the bounce phenomenon occurs in cell A with a larger DC voltage (12 V). In this case with low impurity concentration, $C_{\rm IP}$ induced by high DC driving voltage increases more rapidly than $C_{\rm SC}$ when $t < t_{\rm IP}$ and then decreases quickly owing to the coupling effects from dissociated ions $Q'_{\rm SC,DC}$. However, $C_{\rm SC}$ can still increase after $t_{\rm IP}$ since it has a peak at later time $t_{\rm SC}$. This results in a dip (bounce) in $C_{\rm t}$ between $t_{\rm IP}$ and $t_{\rm SC}$. With the same driving DC voltage (12 V), cell B behaves quite differently as shown in Fig. 4(d). The characteristic of $C_{\rm IP}$ in Fig. 4(d) is essentially the same as illustrated in Fig. 4(c) except for the stronger coupling effect from dissociated ions. Note that the higher impurity concentration results in a higher increasing rate of space-charge capacitance $C_{\rm SC}$ after the voltage is switched on. If the impurity concentration is high enough to make the increasing rate of $C_{\rm SC}$ larger than that of $C_{\rm IP}$, the dip in the curve of $C_{\rm t}$ will disappear and is replaced by a bump as shown in Fig. 4(d). In our experiment, a DC voltage of 12 V is large enough to induce a total capacitance larger than the critical value, $C_{\parallel}/C_{\perp}$, for cell B with 0.5 wt% dopant of TBAI.

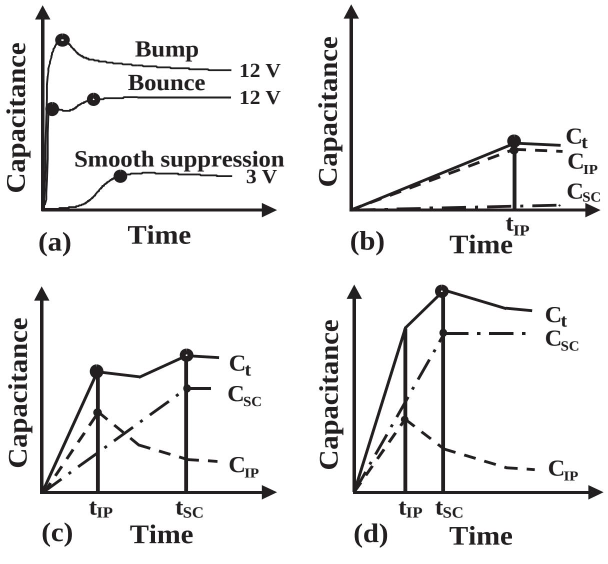


Fig. 4. (a) Measured capacitance replotted from Fig. 1. The schematic diagrams for illustrating the capacitance behaviors in various regimes: (b) regime (1), (c) regime (2), and (d) regime (3).

5. Conclusion

We have investigated the dynamic response of a homogeneous LC cell with a cell-gap of 100 μm. In addition to the smooth suppression effect that is usually expected in a cell driven by a lower DC voltage, we observed the capacitance bump and capacitance bounce for cells driven by a higher DC voltage with higher and lower impurity concentration, respectively. The large amounts of fast ions are responsible for these anomalous behaviors. The DC voltage plays an important role on the dissociation of ions. It also moves an amount of its dissociated fast and slow ionic charges so LC directors experience a gradually decreasing DC voltage and thus $C_{\rm IP}$ also decreases. The ions that can follow the fast alternating fields (1 kHz) and thus gives the space-charge polarization component $C_{\rm SC}$ are mostly fast ions. We finally give a very important conclusion that if a LC cell is impurified by some impurities which offers fast ions, its capacitance behaviors will dramatically different. Another capacitance component contributed from the fast ions must be considered.

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