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Transient current in nematic cells containing a silicon substrate

S I Kucheev

Physics Department, Belgorod State University, Studencheskaya 14 Street,
Belgorod 308007, Russia

E-mail: skucheev@yahoo.com

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Abstract
Transient currents induced by step voltage or polarity reversal of voltage applied to a liquid crystal cell containing a silicon substrate have been investigated. It is shown that the curves of transient current reveal a minimum for negative polarity of dc voltage relative to a silicon substrate of p-type conductivity. The time of the occurrence of the minimum corresponds to the collection of positive ions from the bulk of the liquid crystal at the silicon surface as a result of drift. This is explained by the formation of a highly resistive layer in the silicon under an electric field of positive ions collected at the silicon surface (a field effect). In polarity reversal experiments, a knowledge of the time of the occurrence of the minimum enables us to estimate the mobility of positive ions, which gives a value of 1.4×10^{-11} M^2 Bc^{-1}.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

It is well known that ion transport in liquid crystals influences the display performance. Under external electric field the ions move toward the electrodes in a liquid crystal cell and form inside an electric field that causes flickering [1], image sticking [2] and decreasing voltage holding ratio [3]. In order to explain the rich variety of charge processes in liquid crystal cells, various investigations in differently prepared cells were carried out [4–10]. At present the methods of investigation of ion processes in liquid crystals, including adsorption and desorption, are based on the analyses of transient currents induced by step voltage, polarity reversal, switching off and short-circuiting [5–7, 11], low frequency impedance [12] and atomic absorption [13]. Conventionally in these methods the experimental cells are manufactured with glass plates coated with indium tin oxide (ITO) film. Because of the symmetric electrode conditions, the behavior of positive or negative charges in such a type of cell cannot separately be distinguished. In such experiments the exact contribution of positive or negative ions to the sum current flowing in a cell remains unknown.

To the best of our knowledge, only one previous work had dealt with direct measurement of mobility of positive ions in liquid crystal separately from negative ones. The authors, as they described, used a photoconductor substrate [14] to inject a thin unipolar carrier sheet and hence to measure the transit time of flight needed for ion drift mobility determination. However, a very fast change from the high resistivity of an amorphous selenium sample to the low value under flash illumination at the given voltage applied to the cell with an amorphous selenium substrate can simply cause a transient current, due to the effect of a step voltage not connected with injection phenomena.

Thus, there is a strong need to develop new methods for charge investigation in which the behavior of positive and negative ions in liquid crystal is separated. The main goal of the paper is to show that drift and collection of ions having selected sign (positive in our case) in liquid crystal cause well registered changes in the plots of transient currents in cells containing a silicon substrate. The idea of such a registration is based on well known depletion layer phenomena (see for example [15]) which is key to the understanding of the operation of many types of semiconductor devices. Silicon substrate in a liquid crystal cell plays the role of a smart element detecting the positive ions (in our case). When the positive ions are collected at the silicon surface they push away the charge carriers in silicon from the surface layer into bulk. Therefore, the so-called depletion layer [15, 16] in silicon is formed. Some part of the voltage applied to the cell drops across the depletion layer having a high resistance that gives rise to a minimum of current. In the present work, this idea

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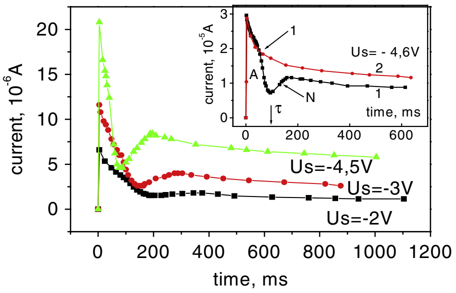

Figure 1. The typical dark transient currents induced by step voltage U_s of negative polarity. Cell thickness and area are 5 μm and $\sim$2.5 cm^2 respectively. Inset shows the curves of current in dark (1) and illuminated (2) cells with an He–Ne laser under the same step voltage U_s.

is utilized for measurement of mobility of positive ions as an example.

2. Experiment

The experimental cell of sandwich type is fabricated from two substrates. One substrate presents an ITO covering on the glass plate. As second substrate monocrystalline silicon of p-type conductivity and 4.5 Ω cm resistivity is used. The equilibrium concentration of major charge carriers in the silicon sample was $\Pi_0 \sim 10^{17}$ cm^{-3}. Before each assembling of the cell, the silicon surface was etched with HF acid, rinsed in distilled water and then dried by hot air flux. The ITO surface was cleared by dimethylformamide solution. Both silicon and ITO surfaces were not covered by any alignment layer. This was done in order to exclude the possible influence of ion redistribution within the alignment layer on depletion layer formation in silicon and maximally decreasing the influence of director reorientation on current [4] in the cell. Cell thickness is defined by the Teflon spacers. Liquid crystal 5CB was filled into the cell in isotropic phase. The transient currents under step voltage or polarity reversal were measured with a wide-band amplifier and a digital storage oscilloscope. The measurements were conducted at room temperature.

3. Results and discussion

Figure 1 shows the typical behavior of the dark transient currents induced by the step voltage U_s with negative polarity relatively to silicon substrate as a function of time. The curves demonstrate the well defined minimum which can be characterized with the time τ of occurrence and the amplitude A, as shown in detail in the inset of figure 1. It can be seen, figure 1, that time τ becomes shorter with increasing applied voltage U_s and, as obtained in the experiments, lies in the range of 70–400 ms for applied voltages in the range of 1–8 V respectively.

The influence of director reorientation on the occurrence of a minimum is excluded for the following reasons. (1) This minimum of current starts to be registered at a step voltage of about 0.5–0.6 V, which is much lower than the voltage needed for the Freederickz transition. (2) The minimum of current is observed at a temperature higher than the clearing point of 5CB. (3) There is no minimum of current under a step voltage for any value with positive polarity (both dark and illuminated conditions), although for appropriate voltages (>2.5 V) the reorientation of nematic liquid crystal takes place that can be well observed with a polarized microscope.

It has been found that the time τ does not depend on the level of illumination. In experiment we used illumination from an He–Ne (0.63 μm, 2 mW) laser. The intensity of illumination has been changed by the rotating polarizer. The illumination of the cell influences the amplitude A of the minimum only. The amplitude A decreases with increasing illumination. As seen in the inset of figure 1 (curve 2) the well illuminated (without polarizer) cell does not demonstrate any minimum.

So, from the step voltage experiment it follows that charge injection [14, 17] under either positive or negative polarity is absent because a minimum in the plot of current in an illuminated cell (in this case an injection must be more intensive than in dark conditions) is not observed (figure 1, inset (curve 2)). We might admit that there is an injection but it is very small and therefore is not detected in the experiment. Thus, there is trivial drift of positive and negative ions towards the corresponding electrodes under step voltage and a minimum of current is not connected with charge injection phenomena. Taking into account that the liquid crystal 5CB in the cell is not sensitive to light, we conclude that the reason for the appearance of a minimum in the plot of current in dark conditions is connected with the formation of the highly resistive layer in silicon.

As is well known, the characteristic time of transient charge processes in silicon with concentration of major carriers equal to n_0 does not exceed several milliseconds [15], which is much shorter than the time τ obtained in experiments, figure 1. Therefore we do not associate the occurrence of a minimum with processes in silicon induced by the external electric field created by an ITO electrode immediately after application of the step voltage. We believe that the highly resistive layer in the silicon substrate, and hence the occurrence of a minimum, is caused by the ion processes taking place in liquid crystal. Let us compare the curves of dark and illuminated cells under the same step voltage U_s, figure 1 (inset). As seen at the beginning of the curves, just after application of the step voltage, the behavior of curves 1 and 2 is practically identical up to the arrow 1. The reason for decreasing current in the illuminated cell, as well as in conventional liquid crystal cells containing two ITO substrates only, is space charge formation due to the drift of carriers towards the electrodes. Therefore we believe that in the dark cell the space charge formation in liquid crystal has also been the leading mechanism of decreasing current in the same time interval (up to the arrow 1, figure 1, inset) and therefore there is no highly resistive layer in the silicon substrate. However, later (after arrow 1) the rate of decreasing current in the dark cell becomes much stronger than in the illuminated one. We associate this strong additional decrease of current in the dark cell, in comparison with the illuminated cell, with the formation of a highly resistive layer in the silicon. Under an applied voltage of negative polarity, the positive ions

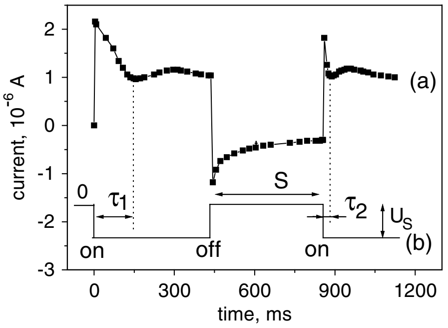

Figure 2. The dark current corresponding to double pulse application. The cell is short-circuited during the interval S. Cell thickness is 5 μm. 'On' and 'off' mean switching on and switching off the voltage $U_s = -2$ V, respectively.

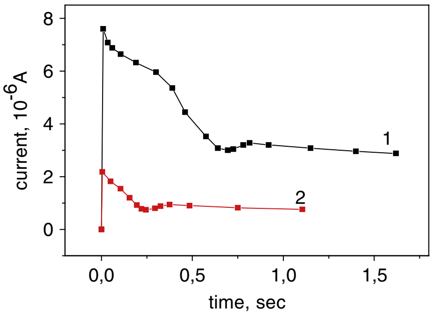

Figure 3. The dark transient currents correspond to (1) polarity reversal from $U = +1.5$ to $U = -2$ V and (2) step voltage of -2 V. The duration of prefield ($U = +1.5$ V) action is 10 s. The curve of current versus time corresponding to prefield $U = +1.5$ V voltage is not shown. Cell thickness is 20 μm.

drift from the bulk of liquid crystal to the silicon surface and accumulate near one. By increasing the number of ions at the silicon surface, the electric field of the positive charge starts to influence the surface conductivity of silicon thanks to a field effect. For silicon of p-type conductivity this electric field pushes major charge carriers (holes) from the surface into the bulk of silicon, i.e. yields a depletion of the surface. Therefore we can interpret the time of the occurrence of a minimum in the step voltage as the time corresponding to maximal collection of positive ions at the silicon surface from the bulk of the liquid crystal.

Because of an electrical contact between silicon and liquid crystal, a certain part of the accumulated positive charge is neutralized via electrochemical reactions. This causes a decreasing value of silicon surface depletion and hence an increasing current, denoted by the arrow N, figure 1 (inset). We assume [11, 18] that the number of positive ions is limited at the given voltage, therefore the short cut corresponding to increasing current is also limited, as seen in the inset of figure 1 (the arrow N).

The above qualitatively described model is confirmed by the following experiments: (1) double pulse application experiment and (2) polarity voltage reversal experiment. Let us consider the double pulse experiment. Figure 2 demonstrates the curve of the current (a) and a schematic illustration of the sequence of the double pulse application (b). Between the pulses of voltage the cell is short-circuited during interval S, figure 2. As can be seen, by the second application of the pulse the time τ_2 is sufficiently less than for the first application of voltage (time τ_1). This is explained as follows. The initial distribution of positive and negative ions in liquid crystal is uniform. After application of the first pulse of voltage, the positive charge is collected from the bulk of the liquid crystal at the silicon surface. This takes a period of time equal to τ_1. When the cell is short-circuited the current changes its polarity, figure 2. During the interval S the accumulated charge relaxes due to recombination and diffusion and therefore its space distribution is changed. If the interval S is not long, the space distribution of charge remains close to the distribution taking place at the moment of electrical short-circuiting the cell. Therefore, in this case, by a second application of voltage the positive ions move and reach the silicon surface more promptly, as seen in figure 2. The increase of interval S up to several minutes leads to a full return of time τ_2 of the occurrence of a minimum to the initial value τ_1. Hence we may conceptually conclude that time τ_2 obtained by a second application of voltage in the double pulse experiment could give important information about the space distribution and relaxation of positive ions.

Figure 3 (curve 1) demonstrates the dark transient current induced by polarity reversal from $+U$ (a so-called prefield) to $-U$. Switching the polarity takes approximately less than 10 ms. As seen in figure 3 (curve 1), the minimum of current is observed. Note, the minimum of current is not observed if the cell is illuminated (the condition of illumination is the same as described in the step voltage experiment). The minimum of current is also not observed in the polarity reversal experiment if the polarity of voltage changes from $-U$ to $+U$ under both dark and illuminated conditions. As seen in figure 3, the time τ (curve 1) is more than for the case of the step voltage experiment (curve 2). The delay in the occurrence of a minimum for the polarity reversal experiment is explained as follows. When the prefield $+U$ relative to silicon acts on the cell the positive ions are collected at the ITO electrode. After the polarity of the external field is reversed, the 'cloud' of positive ions moves toward the silicon surface across the cell. Therefore the distance of flight is on average larger than in the case of the step voltage experiment when ions are collected from the bulk. As a result, the time needed for a positive charge to cover this distance is longer.

Figure 4 demonstrates the dependence of the time τ from the reversal polarity of voltage as a function of applied voltage (versus $1/U$). A straight line can be observed, which means that the occurrence of a minimum of transient current in the cell is caused by movement of mobile ions. The estimation of ion mobility using the formula $\mu = d^2/\tau U$ [17, 19], where d is the cell thickness gives a value of 1.4×10^{-11} M^2 Bc^{-1}. The obtained value of positive ion mobility is in good agreement with the literature data [7, 18, 20–22].

4. Conclusion

The main result of the paper is as follows. The redistribution of ions in nematic liquid crystal under a step voltage or polarity

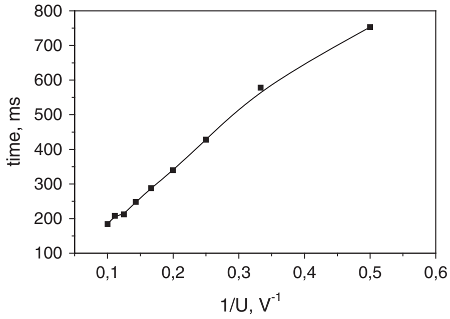

Figure 4. The dependence of time τ as a function of inverse applied voltage U. The polarity is reversed from $U = +2$ V to $-U$. The duration of prefield ($U = +2$ V) action is 10 s. Cell thickness is 5 μm.

reversal in a cell with silicon substrate causes a well registered change in the plot of transient current. In such a type of cell with silicon of p-type conductivity the minimum on the curves of transient currents is observed by negative polarity of applied voltage relative to the silicon substrate only. The minimum of current versus time is explained by the formation of a highly resistive layer in the silicon due to the collection of positive ions in the liquid crystal layer at the silicon surface. The time at which the minimum occurs corresponds to a maximal collection of positive ions at the silicon surface. This method gives the possibility to study the mobile characteristics of positive ions and their contribution in the charge process in liquid crystals separately from negative ions. In the step voltage experiment, the time of the occurrence of a minimum is interpreted as the time of collection of positive ions from the bulk of the liquid crystal. In the case of the polarity reversal experiment, the time of the occurrence of a minimum is interpreted by the flight time of a positive ion 'cloud' from the ITO surface up to the silicon surface across a cell. The estimation of the mobility of positive ions gives a value of 1.4×10^{-11} M^2 Bc^{-1} which is in good agreement with the literature data. A double pulse experiment enables us to study the evolution of the space distribution and relaxation of positive ions. This is based on the finding that the shape of the transient current curve in a double pulse experiment is dependent on the interval of the short-circuiting of the cell.

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