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Shuichi Murakami [a], Hiroyoshi Naito [a], Masahiro Okuda [a] & Akihiko Sugimura [b]

[a] Department of Physics and Electronics, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai, Osaka, 593, Japan

[b] Department of Information Systems Engineering, Osaka Sangyo University, 3-1-1 Nakagaito, Daito, Osaka, 574, Japan

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STEADY STATE CURRENT IN NEMATIC LIQUID CRYSTALS

SHUICHI MURAKAMI, HIROYOSHI NAITO and MASAHIRO OKUDA
Department of Physics and Electronics, Osaka Prefecture University,
1-1 Gakuen-cho, Sakai, Osaka 593, Japan
AKIHIKO SUGIMURA
Department of Information Systems Engineering, Osaka Sangyo University,
3-1-1 Nakagaito, Daito, Osaka 574, Japan

Abstract A steady state current flowing in nematic liquid crystals (NLCs) has been studied for NLC cells with and without polyimide alignment layers. For the cell without the polyimide layers, the steady state current is ascribed to the charge injection from the electrodes and the generation of mobile ions at lower and higher applied voltages, respectively. For the cell with the polyimide layers, on the other hand, the current is much smaller than that of the cell without the polyimide layers. This is due to the fact that the polyimide layers block the charge injection from the electrode to the NLC slab and that the external applied voltage falls entirely in the polyimide layers.

INTRODUCTION

Recently, considerable attention has been directed toward the transport mechanisms of the impurity ions in nematic liquid crystals (NLCs).[1-6] This arises from the fact that the impurity ions in NLCs degrade the performance of NLC displays. Although the knowledge of the ion generation process is of fundamental importance for the understanding of the ion transport mechanisms, the ion generation process in the NLC cells has not been studied extensively.

In this paper, we study the steady state current in NLC cells with and without polyimide alignment layers. Physical processes such as charge injection into NLC slab and ion generation in NLC bulk behind the steady state current are discussed.

EXPERIMENT

The NLC, alignment layers and electrodes used in this study were 5CB, polyimide layers and ITO, respectively. The polyimide layers were coated onto the ITO electrodes. We also prepared NLC cells without the polyimide layers. The area of the electrodes was 2 cm^2. The thicknesses of the NLC layer with and without polyimide layers were 7-15 μm.

We measured the transient current induced by a step voltage using an ammeter (Keithley 617), and determined the steady state current flowing in the cell. The step voltage V was 0.1-15 V. The cell was kept at constant temperatures.

RESULTS AND DISCUSSION

Figure 1(a) shows a typical transient current of an NLC cell without polyimide layers induced by the application of a step voltage of 0.5 V at 303 K. The transient current decreases and reaches the steady state value I_s at about 10^3 s. The applied voltage dependence of the steady state current is shown in Figure 1(b).

In the high applied voltage region ($\gg$1 V) of Figure 1(b), the steady state current for the NLC cell without the polyimide layers varies as $\ln I_s \propto \sqrt{V}$. The applied electric field aligned 5CB molecules in its direction, which was confirmed by the changes in the capacitance of the NLC cell. This phenomenon seems to be due to the Poole-Frenkel effect for ionic carrier generation in 5CB bulk, which is described below.

When the concentration of the neutral molecules is much larger than that of the ions, the chemical formulation can be written as

$$\mathrm{AB} \rightleftharpoons \mathrm{A}^+ + \mathrm{B}^-,$$

for a weakly ionized species dissolved in 5CB. If such an equilibrium system is placed between two electrodes with separation L under a uniform electric field of magnitude E, the electrostatic binding energy of the ion pair U_a decreases by $\beta_{PF}\sqrt{E}$, where β_{PF} is the Poole-Frenkel constant,

$$\beta_{PF} = \sqrt{\frac{q^3}{\pi \epsilon_r \epsilon_0}}, \tag{1}$$

q is the electronic charge, ϵ_r the relative dielectric coefficient, and ϵ_0 the free space permittivity. The steady state current due to the ion generation by the Poole-Frenkel effect[7] is given by

$$I_s = 2qN_0K_0\exp(-\frac{U_a - \beta_{PF}\sqrt{E}}{kT})L, \tag{2}$$

where the factor 2 comes from both positive and negative ions, N_0 the concentration of the neutral molecules, K_0 the ionization rate, k the Boltzmann constant, and T the temperature. If this is the case, the steady state current depends exponentially on the square root of the electric field strength.

β_{PF} is calculated from Equations (1) and (2) to be 1.8×10^{-4} eVcm$^{1/2}$V$^{-1/2}$, where $\epsilon_r = 17.0$ and $E = V/L$, whereas β_{PF} is determined to be 2.0×10^{-4} eVcm$^{1/2}$V$^{-1/2}$ from Figure 1. Since both values are almost equivalent, we consider that the ion generation at the high applied voltages is due to the Poole-Frenkel effect in the 5CB bulk.

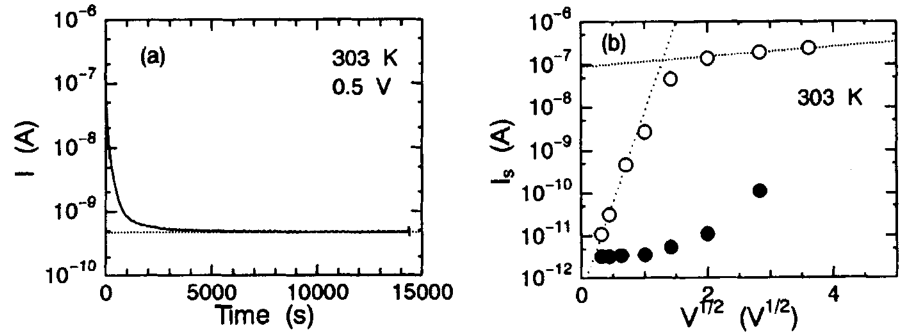

Figure 1. (a) Typical transient current for an NLC cell without the polyimide layers induced by 0.5 V step voltage application at 303 K. (b) Steady state current as a function of the applied voltage for NLC cells with (closed circles) and without (open circles) polyimide alignment layers.

In the low applied voltage region ($\ll$1 V) of Figure 1(b), the steady state current depends exponentially on the square root of the applied voltage as well. However, the slope at the low applied voltages is much larger than that at the high applied voltages, and the applied electric field did not align 5CB molecules, which was manifested from the capacitance measurement.

It is likely that an electric double layer plays an important role in this low applied voltage region. We have found from the dielectric measurement in the ultra-low frequency regime that the Helmholtz double layers are formed at the electrode/5CB interfaces with thickness d.[8] From the measurement of the capacitance of the NLC cell, the effective electric field in the 5CB bulk is also found to approach V/L as the applied voltage increases ($\gg$1 V), whereas the external applied voltage falls entirely in the Helmholtz double layers and vanishes across the 5CB bulk at the low applied voltages ($\ll$ 1 V). The electric field in the Helmholtz double layer at the low applied voltages can be written as

$$E = \frac{V}{2d}. \tag{3}$$

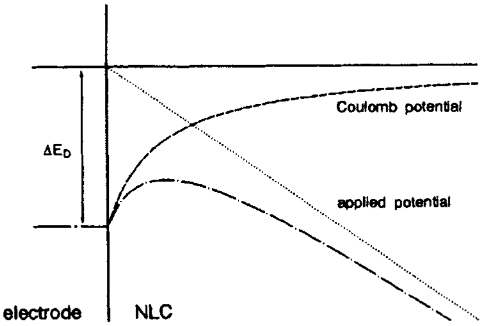

Figure 2. Energy diagram showing the image force for desorbing ions. The distance at the potential maximum from the electrode is calculated to be 0.4 nm at 0.1 V and within the Helmholtz double layer in the present experimental conditions.

The steady state current for the NLC cell without polyimide layers is a few orders of magnitude larger than that for the NLC cell with polyimide layers as shown in Figure 1(b). This is due to the fact that the polyimide layer acts as a blocking layer which prevents charges from injecting from the electrode into the 5CB slab[9] and that the external applied voltage falls entirely in the polyimide layers.[10] It is therefore reasonable to consider that the current for the NLC cell without polyimide layers is attributed to the injection of electronic carriers from the electrode to the 5CB slab. The injected electrons or holes create the negative or positive ions from neutral molecules adsorbed on the electrodes. The electric potential experienced by the ions in the neighborhood of the electrode/5CB interface can be illustrated in Figure 2. It is composed of two parts; the ion image potential, which decreases rapidly as the ion leaves the interface, and the potential associated with the applied electric field.[11] The region between the interface and the potential maximum acts as an ion reservoir. The ions leave this region by escaping over the potential maximum. Considering the lowering of the potential barrier by the applied electric field, which is represented in Equation (3), the steady state current due to the injection can be derived as

$$\begin{aligned} I_s &= I_{s0} \exp(-\frac{\Delta E_D - \beta_s \sqrt{E}}{kT}), \\ \beta_s &= \sqrt{\frac{q^3}{4\pi\epsilon_r\epsilon_0}}, \end{aligned} \tag{4}$$

where I_{s0} is a constant and ΔE_D is the desorption activation energy in the absence of the electric field. It is clear from the above equations that the steady state current depends exponentially on the square root of the electric field, known as the Schottky effect.

From the steady state current in the low applied voltage region ($\ll$1 V) of Figure 1(b), the thickness of the Helmholtz double layer formed at the electrode/5CB interface is estimated to be 1.4 nm by Equations (3) and (4). The double layer thickness is similar to that determined from the dielectric measurement in the ultra-low frequency regime.[8]

CONCLUSIONS

We have measured the steady state currents with and without polyimide alignment layers. The current for the cell with the polyimide layers is a few orders of magnitude smaller than that of the cell without the polyimide layers, which is ascribed to the fact that the polyimide layer acts as a blocking layer to prevent the exchange of charges between electrode and NLC slab and that the external applied voltage falls entirely in the polyimide layers. For the cell without the polyimide layers, the steady state current is found to be due to the charge injection from the electrodes and the generation of mobile ions in NLC bulk in the lower and higher applied voltage regions, respectively. The thickness of the Helmholtz double layer is estimated to be 1.4 nm.

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