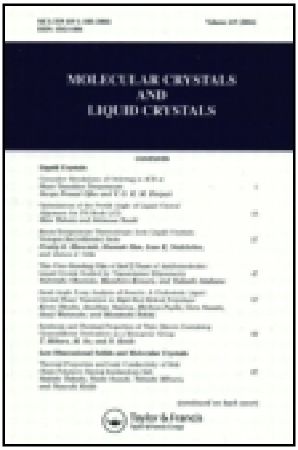

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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To cite this article: M. I. Gritsenko & S. I. Kucheev (2005): Using the Field Effect in Silicon to Study Charge Processes in a Nematic Cell, Molecular Crystals and Liquid Crystals, 426:1, 109-116

To link to this article: http://dx.doi.org/10.1080/15421400590890804

Mol. Cryst. Liq. Cryst., Vol. 426, pp. 109–116, 2005
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ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400590890804

Using the Field Effect in Silicon to Study Charge Processes in a Nematic Cell

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We propose a simple method for the qualitative study of charge processes in a liquid crystal layer at the silicon surface. The method is based on the field effect that has been induced by charges that are localized near the silicon surface. The method is sensitive to the sign of accumulating charge and does allow monitoring a change of the surface charge.

Keywords: field effect; ion surface charge; liquid crystal; silicon

INTRODUCTION

Liquid crystals belong to materials in which ions are unavoidable due to impurities and molecular dissociation. At the solid/liquid crystal interface, the selective ion adsorption can create a surface field which can modify surface properties [1]. Many experimental studies that clearly show the influence of charges on surface phenomena in liquid crystal (LC) are carried out [2–5]. The movement of ions in a typical liquid crystal display can also cause various effects: flickering, sticking, and image degradation [6,7]. The understanding of charge phenomena is therefore of key importance for successful applications of liquid crystals.

In order to study charge phenomena, many methods have been developed [8,9]. The most of them are based on conductivity measurements in different manners. In this paper, we suppose a new method to study the charge processes taking place in nematic cells. In this method, we use the field effect in silicon induced by ions localized in the liquid crystal layer [10].

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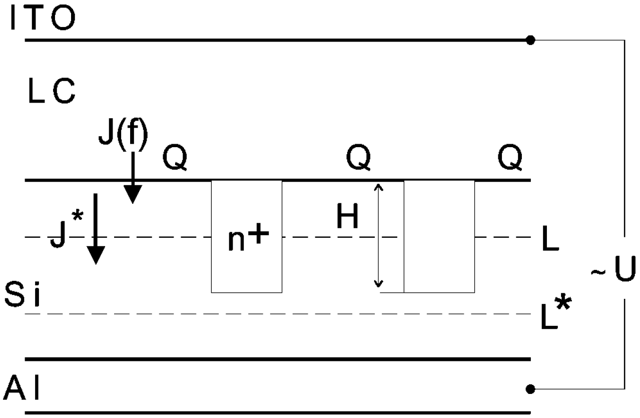


FIGURE 1 Schematic view of the experimental liquid crystal cell. L, L^* – depletion layers, Q – surface charge, and n^+ – high doped pockets.

METHOD

The idea of this method is schematically shown in Figure 1. Under the action of the electric field of the ITO electrode, the surface concentration of major carriers of charge in silicon is changed (the so-called field effect [11]). Surface charges Q change also a surface conductivity of silicon by means of the field effect [10]. Because a nematic layer contacts with the silicon surface, there exists charge exchange through the LC/Si interface, J(f), depending on frequency. A depleted state of the silicon surface is formed only when $J^* > J(f)$, where J^* is the current of major carriers from the surface into the bulk of silicon. The current J(f) depends on the concentration of carriers of charge in LC.

When there is a depleted layer L in silicon, the external voltage U applied to the cell is distributed between the high resistive layer L and LC. On the other hand, it is very difficult to deplete silicon in n^+ pockets (Fig. 1) because of a high concentration of carriers within them. Therefore, the potential relief on the silicon surface is formed in accordance with a voltage drop across the surface resistance that has been visualized by electrooptic effects in LC. So, if $0 < L < H$, where H is the depth of an n^+ pocket, we observe the location of n^+ pockets by means of different electrooptic reactions of the nematic over the n and n^+ surfaces (see Fig. 2).

The n^+ pockets are not visualized by LC in two cases. First, when $L > H$ and, secondly, when $L \sim 0$. In the first case, the voltage drop occurs across the depleted layer under pockets, Figure 1 (L^* case). In this case, the potential relief on the silicon surface is "smooth" and

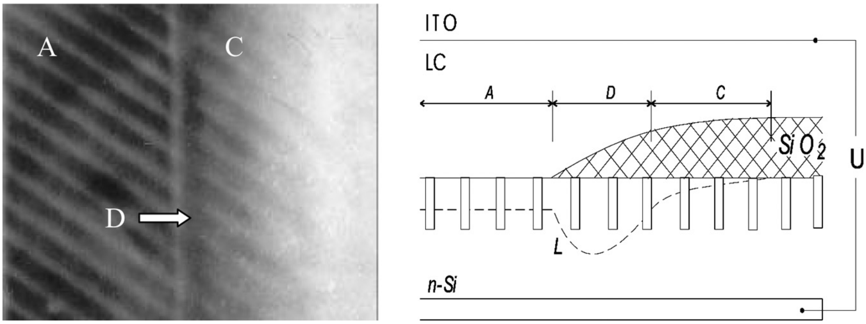


FIGURE 2 Visualization of n^+ pockets (white stripes) located on the open silicon surface (A) and under silicon oxide SiO_2(D,C) in the Al/Si/5CB/ITO structure. D is the area of a very thin SiO_2 film, where $L > H$.

the director distribution is uniform due to the surface initial alignment. Figure 2 (area D) demonstrates the situation when n^+ pockets are not visualized by LC that is due to a decrease of J(f) because of thin SiO_2 on the Si surface. In the second case, the potential relief is also "smooth" because a depleted layer is absent in any place of silicon. These two situations are well distinguished each from other by an electrooptic reaction of the cell under a Ne-He (0.63 mkm, < 2 mW) laser illumination. In the first case, cells are photosensitive, and a LClayer modulates the reflected light in accordance with the intensity distribution in a laser spot on silicon as this takes place in LC spatial light modulators [12]. In the second case, the cells are not photosensitive.

So, having a number of n^+ pockets with different H, we can monitor a change of surface charge by means of different electrooptic reactions of LC over different n^+ pockets.

EXPERIMENT

In our experiment, we used the silicon structure shown in Figure 1. A number of high doped regions, as pockets with equilibrium major carrier density $n^+ \sim 10^{19}\,\text{cm}^{-3}$ and depth $H \sim 264$ nm are formed in a single-crystalline n-type conductivity silicon sample with $n \sim 10^{15}\,\text{cm}^{-3}$. No oriented films covered the silicon surface. Each time, before assembling the cell, the silicon surface has been undergone by the same procedures: etching by HF, washing by distilled water, and drying by a hot air flux. Then the silicon surface has been gently rubbed to create a preferred alignment of the nematic LC. The ITO surface was coated with rubbed polyimide that creates a strong anchoring. LC 5CB was filled by the isotropic phase.

Because the crystalline surfaces of n-silicon and n^+ silicon are identical, the pretilt angle of LC molecules at different places of the silicon surface is the same. If no voltage is applied to the cell, n^+ pockets are not visualized.

RESULTS AND DISCUSSION

Fresh-made Cells

In experiments, we examined twelve fresh-made cells (1–12). By the first switching on of the ac testing voltage, all investigated cells can be separated into three groups using the signs of n^+ pockets visualization and structure photosensitivity. The cells in which n^+ pockets are not visualized and photosensitivity is absent belong to the first group (3, 5, 9, 10, and 12 cells). For these cells, a depleted layer is absent ($L \sim 0$) and we believe that either a positive surface charge Q^+ has been formed during cell preparation or a strong J(f) takes place.

The cells in which n^+ pockets immediately or in tens seconds after switching on the voltage are visualized and their photosensitivity is high belong to the second group (2, 6, and 8 cells). In cells of this group, a negative surface charge Q^- is localized on the silicon surface and, probably, J(f) is small. For these cells, $0 < L < H$.

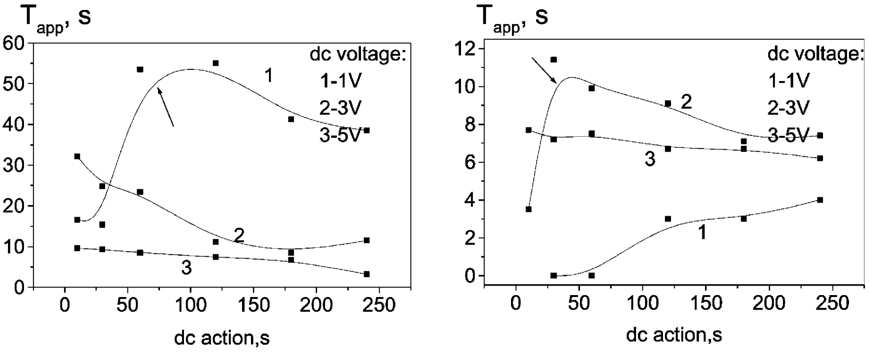
In the third group of cells (1, 4, 7, and 11 cells), n^+ pockets are not visualized, but photosensitivity of structures is high. Obviously, $L > H$ in these cells. This means that there is a negative charge Q^- on the silicon surface and J(f) is also small. So, our experiments have shown that the fresh-made cells demonstrate no tendency to accumulate selectively a surface charge during cell preparation.

Induced Surface Charge

In our experiments, the accumulation of charge at the silicon surface is carried out by applying the external dc voltage to the cell.

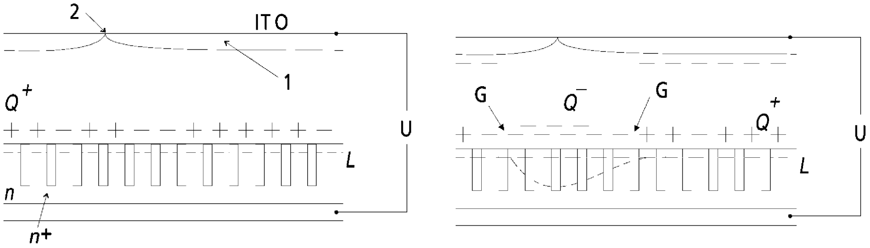
a) "+" *polarity of U on silicon*. For such a polarity of dc voltage, negative ions drift from the bulk toward the silicon surface and are accumulated at the surface. After the dc action, the testing ac voltage is switched on. The influence of the accumulated charge on the depletion of silicon can be observed in the first two types of cells. In the first type of cells, this influence manifests itself by the short-time "appearing" of n^+ pockets. In the second type of cells, the accumulated charge causes either an increase in the image contrast of n^+ pockets or their short-time (tens seconds) "disappearing". The last means that L > H at this moment of time. Figure 3 gives the typical time dependences of the beginning of the n^+ pockets visualization versus the duration of a prior dc voltage action in a cell of the second type. The visualization time T_{app} is proportional to the duration of a dc voltage action only for short periods of time and no high voltages (Fig. 3a, up to the arrow on the first curve). This means that the accumulated charge depletes silicon only and does not cause other effects. However, if voltage is higher or its duration is longer, the visualization time T_{app} becomes lesser, i.e. the cell is restored to the initial state more quickly (see Fig. 3a, curves 2, 3). We believe that, under the action of a high voltage, the process related to a silicon surface modification starts to be realized. For example, the process of Si surface oxidation can play important roles. Obviously, appearing a dielectric film SiO_2 on the silicon surface limits the influence of Q on carriers of charge in silicon.

Figure 3b gives the results of the same measurements but carried out in 15 minutes . It is seen that, under the same conditions of experiment, the restoration time to the n^+ visualization state is no more than ~10 sec. Qualitatively, the cell exhibits the same behavior as that for a fresh-made cell. That is, for small voltages, one observes the proportionality between the return time and the prior dc action (Fig. 3b, curve 1 and curve 2 up to the arrow), but this proportionality is also broken for high voltages (curve 3). We believe that the change of the silicon surface happened during



a) b)

FIGURE 3 Dependence of the n^+ pockets visualization time, T_{app}, versus the duration of a prior dc voltage action. Testing ac voltage: 10^5 Hz, 4.3 V. a) fresh-made cell. b) The same measurements in 15 min.



a) b)

FIGURE 4 Schematic representation of the restoration of the n^+ visualization and structure photosensitivity. Q^+ – positive surface charge initially induced by dc action. Q^- – charge accumulated due to the bias because of the rectification of ac voltage on the Schottky barrier. G – boundary between the photosensitive and nonphotosensitive areas. 1 – polyimide film. 2 – defect of the polyimide film. a) at the the first moment after switching on the ac voltage. b) at a certain time.

the first series of measurements continues to influence the silicon depletion. Cells return fully to initial states in several hours.

In the third type of cells, the influence of surface negative charge Q induced on silicon is not observed because $L > H$.

b) " – "*polarity of U on silicon*. When voltage of such a polarity acts on the structure, positive ions drift toward the silicon surface. A charge Q^+ accumulated at the silicon surface induces a decrease in L. The experiments show that the visualization and photosensitivity are simultaneously absent in cells of the second type after the dc voltage action, when the testing ac voltage is switched on the n^+ pockets. This means that $L \sim 0$ at this moment of time (Fig. 4a). As far as the surface charge Q^+ relaxes, the n^+ visualization and photosensitivity of the structure are restored. One of the possible mechanisms of Q^+ relaxation is the neutralization of Q^+ caused by the accumulation of a negative ion Q^- due to the bias taking place because of the ac voltage rectification on the Si/Al Schottky barrier. The beginning of such a neutralization process is well observed in cells containing defects (2) of polyimide film (1) on the ITO surface, (Fig. 4). The transition to the photosensitive state (and n^+ visualization also) starts in the vicinity of defects. Further, the photosensitive area extends covering all surface. The boundary (G) between the photosensitive area and nonphotosensitive one on the silicon surface is well contrast and its movement is well observed. The structure conductivity in the vicinity of defects

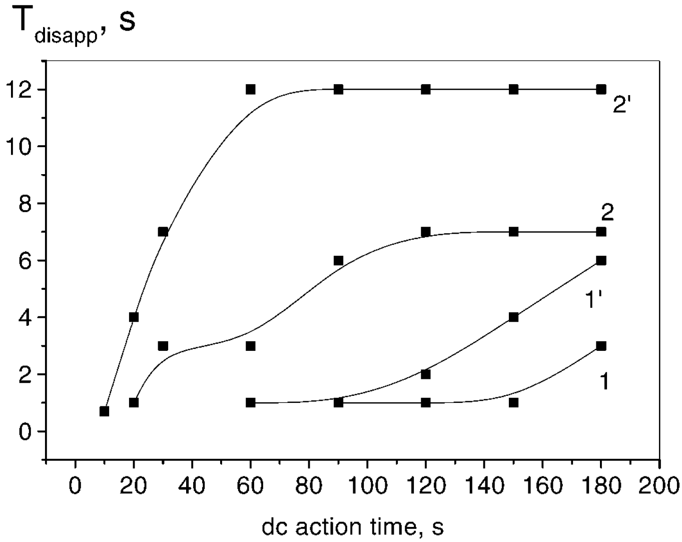


FIGURE 5 Time dependence of n + pockets "disappearance" versus prior dc voltage action. Voltage: 1, 1′ – 1′V, 2, 2′ – 1.5 V. Curves 1, 2 and 1′, 2′ correspond to the measurements carried out with the fresh-made cell and in 15 minutes, respectively. Testing voltage: 10^5 Hz, 4.5 V.

of the polyimide film is larger than that near defectless areas. Therefore, the processes of negative charge accumulation and neutralization go here more intensively.

In order to visualize n^+ pockets in the third type of cells, it is necessary to apply the voltage of negative polarity to silicon. In this case, positive charge Q^+ accumulates at the silicon surface and, therefore, it is very easy to obtain the situations where $L < H$.

Figure 5 demonstrates typical dependences for cells belonging to the third type, when n^+ pockets had been immediately visualized by switching on the ac testing voltage. As far as Q^+ relaxes, n^+ pockets "disappear". As seen in Figure 5 (curves 1, 2), the restoration time (the disappearance of n^+ pockets) is proportional in the general case to the duration of voltage action and its value. This means that the accumulated charge is also proportional to the duration and value of the acting dc voltage.

We believe that there is process of positive charge adsorption on silicon surface. When the experiment is repeated in 15 minutes (Fig. 5, curves 1′, 2′), the lesser duration of dc voltage action is required in order to achieve the same times of n^+ "disappearance" that corresponds to the fresh-made cell situation.

CONCLUSION

We have shown that the field effect in silicon can be used to monitor changes of surface charge in a liquid crystal. We used the special silicon structure in which the electrooptic reaction of the nematic over high doped pockets of depth H depends only on the relation between the depleted layer width L and H. The method enables one to register the accumulation of ion charges of both signs under the action of a respective dc voltage.

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