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## Liquid Crystals

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A. M. Biradar<sup>a</sup>; S. Hiller<sup>a</sup>; W. Haase<sup>a</sup>; E. P. Haridas<sup>b</sup>; S. S. Bawa<sup>b</sup>; S. Chandra<sup>b</sup>

<sup>a</sup> Institute für Physikalische Chemie, Technische Hochschule Darmstadt, Darmstadt, Germany <sup>b</sup> National Physical Laboratory, New Delhi, India

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# Switching dynamics of first order phase transition FLCs on a polymer rubbed surface

by A. M. BIRADAR\*, S. HILLER and W. HAASE

Institute für Physikalische Chemie, Technische Hochschule Darmstadt,  
Petersenstr. 20, 64287 Darmstadt, Germany

E. P. HARIDAS, S. S. BAWA and S. CHANDRA

National Physical Laboratory, Dr. K. S. Krishnan Road, New Delhi-110 012,  
India

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The switching dynamics in a first order phase transition ferroelectric liquid crystal, possessing a chiral nematic to smectic C\* phase transition, have been studied in thin (4 μm) polymer rubbed cells. It has been observed that when one surface of the cell is coated with polymer and strongly rubbed, then a monodomain sample is obtained with asymmetric switching dynamics due to surface anchoring effects. When both the surfaces of the cell are polymer coated and strongly rubbed, then two well aligned domains are formed in the material. It has been observed that the directions of the spontaneous polarization in the two domains are pointed oppositely to each other. The results have been analysed by optical and electrical switching methods and are discussed.

## 1. Introduction

The problem of interfacial properties of liquid crystals is not only of fundamental interest, but also of practical importance to the design and fabrication of liquid crystal devices. It is well known that different techniques [1–4] have been used for aligning ferroelectric liquid crystal (FLC) molecules other than the well known technique of a polymer rubbed surface. Amongst the surface alignment techniques, the use of rubbed polymers is of particular interest because of its feasibility for preparing large areas and mass production devices, although the polymer rubbed alignment creates high surface anchoring at the boundary and generates the zig-zag defects, due to the formation of the chevron structure, which affect the contrast of the devices. It has been recognized that the anchoring structure formed at the interface of solid substrates provides a direct means for controlling the bulk ordering and the behaviour of the liquid crystal molecules, and in turn a wide variety of electro-optical properties are affected. However, the actual alignment mechanism and its relationship to the treated substrate, as well as the correlation between bulk ordering and surface anchoring effects remain important subjects of continued active research.

Mainly two types of FLCs are reported in literature.

These are (i) the second order phase transition type having the phase sequence: crystalline(Cr)–smectic C\* (S<sub>C</sub><sup>\*</sup>)–smectic A(S<sub>A</sub>)–nematic (N)–isotropic(I) and (ii) the first order phase transition type having the phase sequence: Cr–S<sub>C</sub><sup>\*</sup>–N\*–I. Extensive research work has been done on the first type, whereas very little is known about the second type because it is not very easy to align these FLCs on polymer rubbed surfaces. In the first type, the long axes of the molecules are oriented parallel to the rubbing direction as the material cools from isotropic to S<sub>A</sub> phase, figure 1(a), and smectic layers form perpendicular to it. Further cooling of the aligned S<sub>A</sub> phase into the more ordered S<sub>C</sub><sup>\*</sup> phase preserves the layered structure and the molecules undergo a tilt with respect to the smectic layer normal and the rubbing direction, figure 1(b). In the FLCs possessing N\* to S<sub>C</sub><sup>\*</sup> transitions, the LC molecules are also aligned along the rubbing direction when the material is cooled down from isotropic to N\* phase, figure 1(c). On further cooling to the S<sub>C</sub><sup>\*</sup> phase, the alignment is not retained because of the fact that the helical axis in the planar (homogeneously) aligned N\* phase lies perpendicular to the electrode surface, whereas the helical axis in the planar aligned S<sub>C</sub><sup>\*</sup> phase lies in the plane of the surface, resulting in the formation of a multidomain structure. However, in the presence of a polymer rubbed surface and then by applying an ac electric field just below the transition temperature of N\* to S<sub>C</sub><sup>\*</sup> phase, this kind of

\*Author for correspondence (in Delhi).

FLC can be aligned in the  $S_C^*$  phase. The LC molecules near the polymer rubbed surface act like nucleating centres for aligning the bulk molecules in the presence of an electric field. The LC molecules in this case are aligned along the rubbing direction and smectic layer planes are tilted with respect to it, figure 1 (d). Because of this, the surface effect due to the polymer rubbed surface is more dominant in these materials as the molecules have to switch from the anchored state (along the rubbing direction) to the unanchored state, resulting in asymmetric switching dynamics. This surface anchoring effect will be more dominant in thin cells.

In this article we report the investigation of the switching dynamics in a first order phase transition FLC material on polymer rubbed surfaces using thin ( $4\ \mu\text{m}$ ) samples. The static switching response had been studied by optical microscopy and the dynamic switching characteristics were analysed using a triangular wave method in the smectic  $C^*$  phase.

## 2. Experimental

Transparent conducting indium tin oxide (ITO) glass substrates were initially treated with adhesion promoter

(silane solution) and polymer (Nylon 66) and then rubbed along the desired direction to obtain the homogeneous alignment of ferroelectric liquid crystal molecules. Weakly and strongly rubbed surfaces (anchored surfaces) were prepared by varying the distance between the glass substrate and the rubbing block which is wrapped in a velvet cloth [5]. Two types of samples were prepared. In the first type, one electrode was treated with polymer and strongly rubbed, whereas the other electrode was left untreated. In the second type, both electrodes were polymer coated and strongly rubbed. The distance between the glass plates was maintained around  $4\ \mu\text{m}$  by means of a mylar spacer. The large tilt angle FLC material CS-2004 (Chisso Corporation, Japan) which shows a first order phase transition, used in these studies has the phase sequence:

$$\text{Cr } -9^\circ\text{C } S_C^* 62^\circ\text{C } N^* 71^\circ\text{C } I$$

The FLC material was introduced into a cell by means of capillary action at an elevated temperature to ensure that filling took place in the isotropic phase. Well aligned samples were obtained by applying an ac field just below

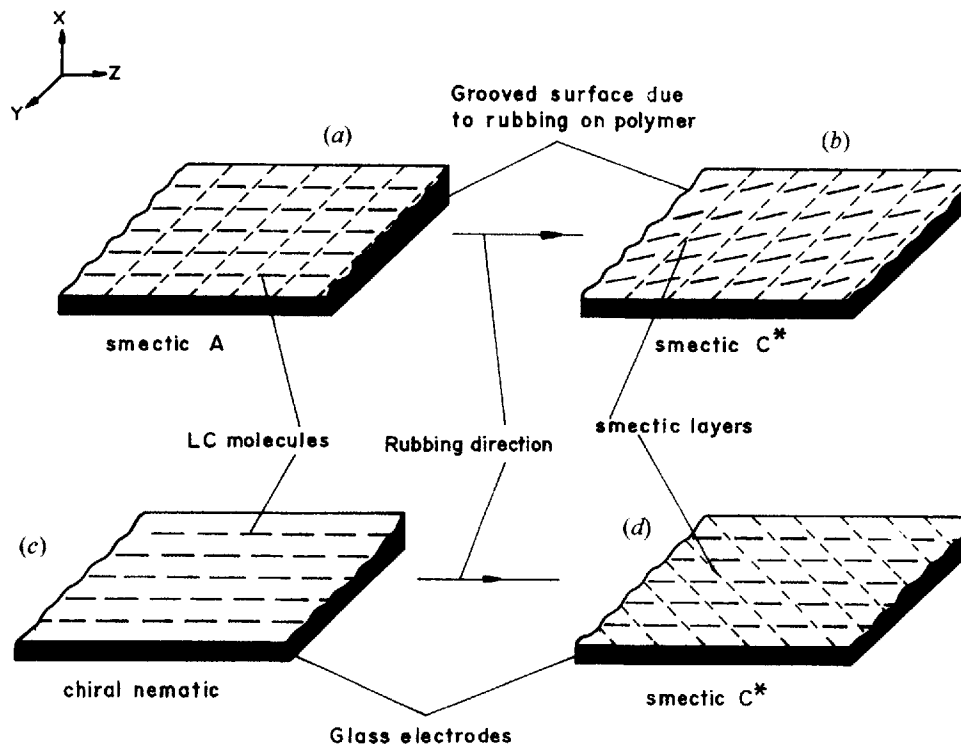


Figure 1. Molecular arrangement for planar alignment in second and first order phase transition FLC materials. —lines define the smectic layers aligned along the  $Y$ -direction, i.e. perpendicular to the glass electrodes. The smectic layer normal is in the  $ZX$  plane (not shown in the figure). The rubbing direction is along the  $Z$ -axis. The molecular arrangement in second order FLCs possessing a  $S_A$  to  $S_C^*$  phase transition is shown in (a)  $S_A$  phase and (b)  $S_C^*$  phase, where the smectic layer normal coincides with the rubbing direction and the LC molecules are tilted with respect to the layer normal or rubbing direction in the  $ZX$  plane. The molecular arrangement in first order FLCs, possessing a  $N^*$  to  $S_C^*$  phase transition is shown in (c)  $N^*$  phase and (d)  $S_C^*$  phase, where the LC molecules are along the rubbing direction, but the smectic layer normal makes an angle of  $44^\circ$  (tilt angle of the material) to the rubbing direction or the LC molecules in the  $ZX$  plane.

the  $N^*-S_C^*$  phase transition temperature. The details for this homogeneous alignment procedure in this material were reported elsewhere [6]. However, in the cells where both electrodes were coated with polymer and strongly rubbed, two domains were obtained in this type of FLC material. The static and dynamic switching response for strongly rubbed surfaces of the electrodes of the FLC cell was studied by viewing samples using a polarizing microscope (Olympus BH2). The transmission of the normally incident light through the samples was monitored with a photodiode. The current response behaviour using triangular wave forms was analysed by using a storage oscilloscope (ECIL OS 768-S).

### 3. Results and discussion

A monodomain sample of a ferroelectric liquid crystal, possessing an  $N^*$  to smectic  $C^*$  phase transition, can be prepared when one surface of the substrate is treated with polymer and strongly rubbed, keeping the other substrate untreated. Such samples show an asymmetric switching response due to the anchoring effect on the rubbed surface. Figure 2 (a) shows the optical micrograph taken in the monostable state and figure 2 (b) shows the polarization reversal current response by when a triangular wave is applied. The asymmetric switching response behaviour is clearly seen when one surface of the cell is coated with polymer and rubbed. It should be mentioned here that the formation of a chevron structure is also clearly seen under the polarizing microscope in the first order phase transition FLC material as shown in figure 2 (c,d), although chevron formation is most common in second order phase trans-

ition FLCs in polymer rubbed cells. The only difference in a first order FLC material is that the zig-zag defects due to the formation of the chevron structure are comparatively low in number, firstly due to the absence of the  $S_A$  phase and secondly as the alignment is obtained in the presence of an ac electric field. By contrast, in second order phase transition FLCs, the smectic layers are fixed, but the liquid crystal molecules are tilted with respect to the smectic layer normal when cooled down from  $S_A$  to  $S_C^*$  phase in polymer rubbed cells.

In the present investigation, the distance between the substrate and the rubbing block was varied to get a highly anchored surface [7] in the cell where only one surface is polymer coated and rubbed. When both the surfaces of the cell are polymer coated and both are strongly rubbed, two domains would be formed in the presence of an electric field [8]. However, if both surfaces of the cell have a different anchoring strength (i.e. a different rubbing strength) then one domain grows and the other domain diminishes in the presence of an applied ac field, but it requires a very high field and a longer time to grow a single monodomain. This means that if both the surfaces have a strong anchoring (rubbing) strength, then two domains would be formed irrespective of electric field magnitude. Here one domain grows from the top electrode and the molecules are aligned along the rubbing direction and the smectic layers are tilted by  $44^\circ$  (tilt angle of the material) to one side of the rubbing direction. The other domain grows from the bottom electrode in which the molecules are also aligned along the rubbing direction itself, but the smectic layers are tilted to the other side of the rubbing direction by  $44^\circ$ , as seen in the figure 3. It is interesting to see that in the two domain sample, the spontaneous polarizations in the two domains are pointed in opposite directions. This is confirmed by the fact that when a dc field is applied to the sample with negative polarity to one of the electrodes, only one domain shows the switching characteristics, as shown in figure 3 ( $A_1=0$  V,  $A_2=3$  V,  $A_3=6$  V and  $A_4=10$  V), and when positive polarity is applied, the other domain shows switching characteristics (figure 3:  $B_1=0$  V,  $B_2=3$  V,  $B_3=6$  V and  $B_4=10$  V). As seen in the figure, both the domains are in the dark state when there is no field applied to the sample. Both domains of the cell, let us call them domain 'A' and domain 'B', are in the monostable state as the thickness of the cell ( $4\mu\text{m}$ ) is very small compared to the helical pitch value ( $15\mu\text{m}$ ) of the FLC material. At about 3 V, with negative polarity to the bottom electrode, the smectic layers are in the untwisted form, resulting in a bright state in domain A [9]. As the voltage is increased, the molecular reorientation starts in domain A, resulting in the dark state for high dc field (10 V) due to complete switching of the molecules,

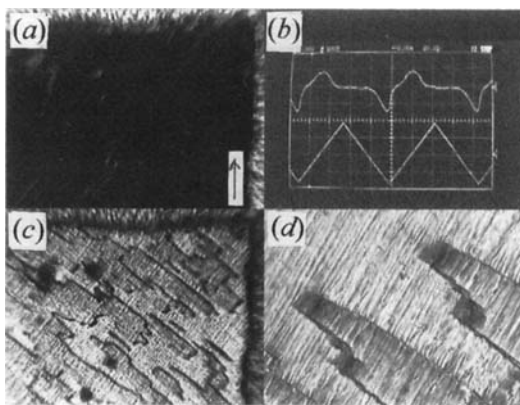


Figure 2. (a) Optical micrograph ( $2.5\times$ ) of a monodomain cell where one electrode is coated with polymer and rubbed ( $\rightarrow$  indicates the rubbing direction) and (b) corresponding polarization reversal current response of a triangular wave form, showing the asymmetric switching response (applied voltage =  $20 V_{pp}$  at 10 Hz frequency). Optical micrograph showing the zig-zag defects due to the formation of a chevron structure (c) at low magnification ( $2.5\times$ ) and (d) at high magnification ( $32\times$ ) at 0.3 V.

whereas domain B is unaffected (stable state). When +ve polarity field is applied to the bottom electrode, then domain B shows the switching characteristics. Figure 4 also shows the grey-scale characteristics in both the domains when fields with negative and positive polarity are applied to one of the electrodes. Detailed studies of grey-scale characteristics in highly anchored surfaces of single monodomain samples have been reported earlier [10, 11].

The static and dynamic switching behaviour in the two domain cell is explained by considering the geometry shown in figure 5. To show the switching behaviour in both the domains, two molecules are considered, one from each of the two domains. When a dc field with negative polarity is applied to the bottom electrode, then the molecules in domain A are rotated by  $88^\circ$  (twice the

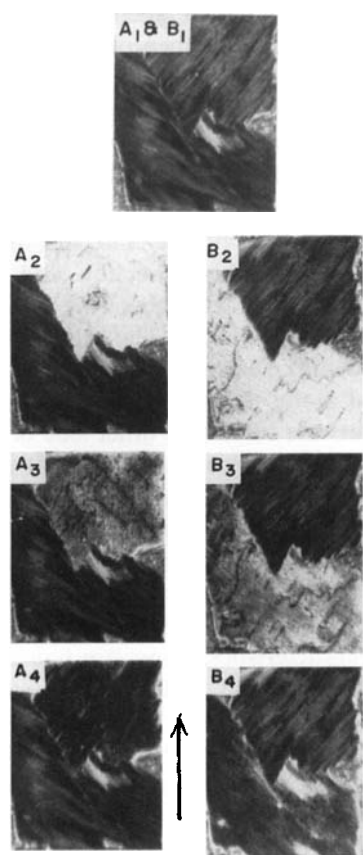


Figure 3. Optical micrograph showing two domains in the FLC cell where both the electrodes are polymer coated and strongly rubbed ( $\rightarrow$  indicates the rubbing direction). One domain shows the switching characteristics when a dc field with negative polarity is applied to the bottom electrode of the cell, i.e.  $A_1=0$  V,  $A_2=3$  V,  $A_3=6$  V and  $A_4=10$  V. The switching characteristics in the second domain are given when a positive polarity is applied to the bottom electrode, i.e.  $B_1=0$  V,  $B_2=3$  V,  $B_3=6$  V and  $B_4=10$  V.

tilt angle), i.e. position D in the figure. The optic axis in domain A would be along D, whereas the optic axis in domain B would be along R (along the rubbing direction). Since the  $P_s$  in domain B is in the opposite direction to that in domain A, negative polarity to the bottom electrode does not change the position of the molecules in domain B. The reverse is the case when the polarity of the field is changed; i.e. the optic axis in domain A will be along the direction R and the optic axis of domain B will be along the direction U.

The dynamic switching behaviour in the two domain cell can be better studied by applying a triangular wave form than a square wave as the change in applied voltage is linear with time in the case of triangular waves. Let us analyse how the positive and negative polarity of the triangular wave affect the current signal due to the spontaneous polarization reversal in the two domain cell as shown in figure 6.

Initially, in both the domains, the molecules are along the rubbing direction with  $P_s$  pointing in opposite directions. When a +ve polarity of the triangular wave is applied to the bottom electrode, then there would not be any change in the polarization reversal current in domain A as the applied field and the  $P_s$  (pointing up, i.e. pointing out of the page) are in the same direction. However, in domain B, the  $P_s$  (pointing down, i.e. pointing into the page) and electric field are in the opposite direction, resulting in the appearance of a peak due to the polarization reversal current. If one looks carefully, the  $P_s$  directions in both the domains are now pointing up (out of the page) and the position of the molecules in domain A is along R and in domain B it is along U, figure 5.

When a negative polarity of the triangular wave is applied to the bottom electrode, then there would be two peaks due to the polarization reversal current, as the  $P_s$  in both the domains were pointing up. In this case the molecules in domain A have to be reoriented from the direction R to D and in domain B from direction U to R. This means that the molecules in domain A are reoriented from the anchored state (rubbing direction) to the unanchored state (i.e. position D). Therefore, the threshold voltage needed for polarization reversal in domain A would be more than that in domain B, and hence the peak due to domain B will appear first as shown in figure 6. The direction of  $P_s$  in both the domains will be pointing down in this case.

Once again, when the +ve polarity is applied to the bottom electrode, then the reverse phenomena occur, i.e. switching of molecules from the anchored to the unanchored state occurs in domain B, and unanchored to anchored switching occurs in domain A, resulting in the appearance of two peaks due to the polarization reversal

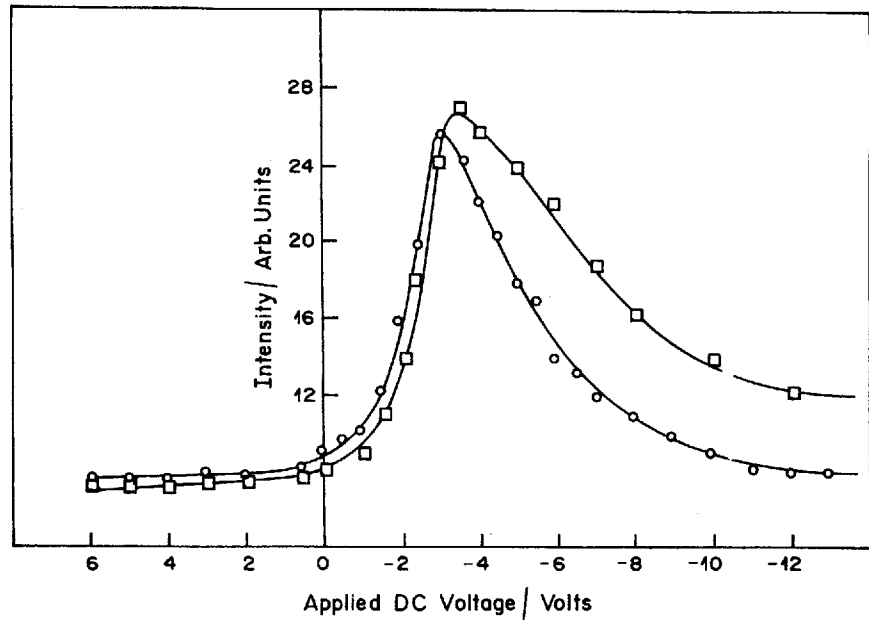


Figure 4. The grey scale characteristics (optical transmission vs. applied voltage) in a two domain cell. (○) dc field with negative polarity applied to the bottom electrode, i.e. optical transmission through the first domain (A); (□) positive polarity applied to the bottom electrode, i.e. optical transmission through the second domain (B).

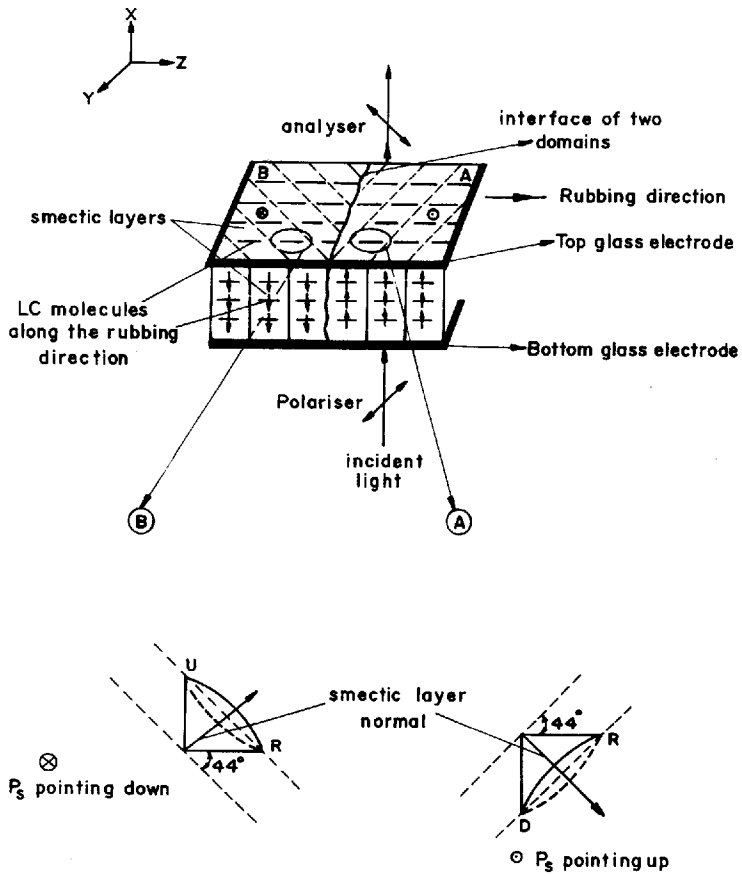


Figure 5. Geometry of the cell showing the position of the smectic layers and the LC molecules in a two domain cell. ⊙ shows the direction of  $P_s$  which is pointing out of the plane in domain A; ⊗ shows the direction of  $P_s$  which is pointing into the plane in domain B. The mechanisms of switching in both domains (B, A) are shown separately by considering one molecule each from the respective domains. In domain B the position of molecules while switching is along R (rubbing direction) and along U (X direction). The smectic layers are perpendicular to the plane of the page and the smectic layer normal is in the plane of the page.

current, with the peak due to domain A coming first as shown in figure 6.

Indeed in the present investigation, two peaks due to the polarization reversal current have been observed

when a triangular wave form is applied to the two domain cell as seen in figure 7, suggesting that the direction of spontaneous polarization in one domain is pointed oppositely to that in the other. Certainly these

Figure 6. Schematic behaviour of the spontaneous polarization reversal current when a triangular wave form is applied to the two domain cell. (A) and (B) indicate the polarization reversal peaks due to the domains A and B, respectively.

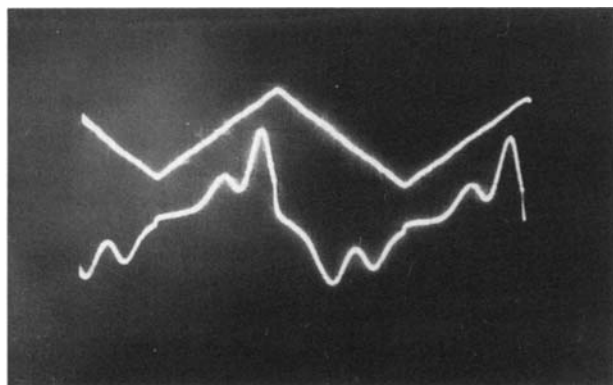
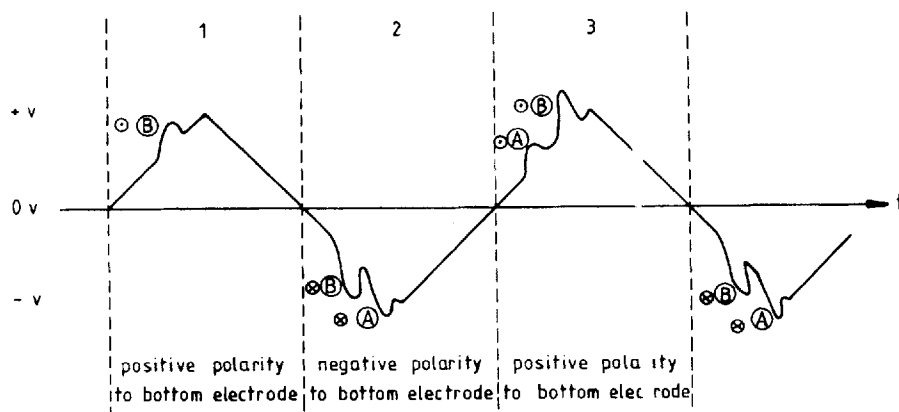


Figure 7. Polarization reversal current due to a triangular wave at an applied frequency of 10 Hz and  $V_{pp} = 20$  V in the two domain cell.

two peaks are not due to the surface and bulk effects of the FLC molecules as the two peaks do not appear in a single monodomain cell such as that prepared by coating both the electrodes and rubbing. In order to obtain a single monodomain in such cells, the rubbing strength on one of the electrodes should be higher than that on the other.

#### 4. Conclusions

In conclusion, it can be said that when both electrodes of the cell are coated with polymer and strongly rubbed, then two domains are formed in the presence of an electric field in thin samples of first order phase transition FLC materials possessing a chiral nematic to  $S_C^*$  phase transition. In the two domain cell the direction of the spontaneous polarization points in opposite directions in the two domains.

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