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The influence of ionic and elastic effects on partial switching in ferroelectric liquid crystal devices

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The simultaneous influences of elastic stress and ionic fields on switching in ferroelectric liquid crystals are considered. Experiments are performed which show that the combined influences can be quite complex. When a reset pulse is applied, it can enhance or decrease the previous ionic field, as well as change the elastic state of the pixel so that when the reset and switching pulses are close together, the combination of these effects influences the result significantly. In some situations, the outcome from simple partial switching schemes cannot be explained from ionic and elastic effects; we suggest a surface switching effect in this case.

1. Introduction

Although nematic liquid crystal devices are now at a well-developed stage, there is still interest in alternative liquid crystal technologies. This is largely because of the expensive production costs of large area devices which one would like to circumvent. These production costs often originate from the thin film transistors and thin film colour filters used in the display devices. One of the interesting alternatives to the currently used nematic liquid crystals is the development of ferroelectric liquid crystal devices. These have considerable potential, and could overcome some of the expensive difficulties with the use of nematic technology. Firstly, the switching mechanism is bistable, which allows (in principle) the development of large area passively addressed devices, saving the large production costs of thin film transistors. In addition the ferroelectric liquid crystal switching is (at least at its basic level) much faster than that in nematic liquid crystal devices, with switching times of 10's–100's μs rather than 10's–100's ms; this could allow sequential colour to be used rather than expensive colour filters.

Even though ferroelectric liquid crystals have these apparent advantages, they are not widely used in devices. This is because there are also a number of difficulties in their application, including the understanding and control of alignment, switching mechanisms and grey scale. While a number of approaches to these problems exist, it is difficult to move forward into production without a fuller understanding. Liquid crystal alignment is generally controlled by treating the surfaces of glass plates forming the device with a thin layer of polymer, which is unidirectionally brushed in the desired alignment direction. The interaction between this and the liquid crystal is still not fully understood, and with the additional complications of the structure in ferroelectric liquid crystals, this means that alignment of the materials is rather a black art. Switching in ferroelectric devices is also difficult to control, with complicated dependencies on the alignment, device structure and previous switched states. The latter effect is a considerable difficulty in display development, as these 'memory' effects lead to the sticking of pixels. In addition, it is important for display devices to be able to show a grey scale, which is difficult to achieve with ferroelectric liquid crystals due to their intrinsic bistability. This problem has to be overcome, and there are various approaches including sub-pixellation, temporal dither and partial switching of a device [1–10]. In the development of partial switching it is again important to understand the switching mechanism as fully as possible.

The switching between states in ferroelectric liquid crystal devices takes place through the formation and evolution of domains. This is general for most materials and alignments used, although the exact process does vary. For the interesting case of C2 alignment (defined below), the switching between states consists of a reorientation in the device into a pre-switched stressed-state, where the bulk of the directors have moved in response to an applied field, but the director at the chevron interface has remained unswitched. This is followed by switching at the chevron interface which is seen as the formation of domains. These domain switched areas then grow and coalesce resulting

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in a fully switched pixel. Although the dynamics of domain switching is well understood and repeatable with square wave addressing, the situation is more complicated in a real addressing scheme, because the device receives a sequence of pulses and the state from which a device is switching can in general vary. Because of this, it is common to apply a reset pulse before the application of switching pulses so that the device is in a well-defined uniform elastic state. Even then, previous states influence the switching, because ionic impurities within devices drift to compensate the spontaneous polarization and set up fields which are present even after a reset pulse. Thus a combination of processes (elastic and ionic) are involved in switching, which need to be considered together.

Previous studies of switching have tended to concentrate on domains, elastic effects or ionic effects, but have not generally considered all effects simultaneously. Ouchi *et al.*, Zhuang *et al.*, Maclennan *et al.*, and Xue *et al.*, have studied domain switching under simple drive conditions, mostly for splayed devices, including demonstration of the director profiles present during switching through the use of spectroscopic polarized microscopy [11–14]. The stressed states present during domain switching in C2 aligned devices have also been studied [15]. Several groups have studied bulk switching and have demonstrated that ionic influences can cause memorization and reverse switching [16–20]. Yang *et al.* include the influence of ions in a one dimensional (i.e. bulk) switching model [16]. This and other one dimensional models have been quite successful in their ability to reproduce what is seen in real devices; given that the real switching mechanism is through domain formation, this is perhaps surprising. Maltese *et al.*, while developing a multi-domain grey scale, attributed previous state dependencies of partial switching to ionic content and had to superimpose a high frequency field and apply multiple reset pulses to decrease this effect [8]. This study did not however consider the elastic effects in switching which can be of considerable importance in the partial switching regime due to the extreme sensitivity to various influences. Here we aim to investigate the results of partial switching sequences on a time scale where both elastic and ionic effects are present by examining the effects of differing delays between the reset and switching pulses and the effects of differing starting states, as would be the case in real display devices.

2. Experimental

The liquid crystal device used in the work here consists of a 2 μm thick layer of the ferroelectric liquid crystal ZLI 4655 (Merck) contained between glass plates. These are treated before assembly with a surface alignment polymer which gives a small pretilt to the liquid crystal, leading to a device with a C2 type structure. In this structure the smectic layering forms a chevron with the layers tilted away from the surface alignment tilt direction. This allows the director near the surface to fulfil the constraints of lying on the smectic cone and in the surface alignment direction. There are then two allowed positions at the chevron interface which can be switched between through the formation and evolution of domains as discussed above.

In order to study the switching, this device is placed in a stroboscopic polarizing microscope. This microscope is illuminated with a short duration flash lamp (duration < 1 μs) and images the cell on to a CCD camera connected to a computer frame grabber. Timing the flash lamp and frame grabber allows pictures of the domain formation, evolution etc. to be obtained at any desired point in the switching sequence. The image can then be imported into an image processing package for analysis. Here we mostly consider the switched area of domains after a sequence of pulses. In order to measure this, a threshold between the domain and background regions is determined for the image and then the pixels above and below this are counted. Dividing the numbers by the total number of pixels in the image allows the percentage of switched area to be determined.

The pulse sequence for addressing the device is derived from an arbitrary waveform generator. This allows a wide range of sequences to be used, although all of those discussed here are relatively simple, consisting of a reset pulse (or series of two reset pulses) followed by a switching pulse. The reset pulse is varied (generally in amplitude), and the switching pulse is chosen to lead to a partially switched state in the device. This is of direct interest in the study of potential partial switching schemes for grey scale production, and is also a sensitive means of probing the influence of the reset pulse on the switching process. Data are normally taken a few hundred ms after the pulse sequence in order to allow a true equilibrium to develop in the switched state.

Before application of a switching sequence the device is set into one of the two relaxed switched states. (For convenience these states are termed the relaxed black or relaxed white state, although neither appears saturated in the polarizing microscope.) In order to obtain these reliably from any previous state, the response of the ionic field is used. This is done by switching and holding the device in the opposite direction to the required state, thus setting up a reverse stabilizing ionic field. When the external applied voltage is removed, the device then switches back into the desired state in response to the field set up by the ions. The device is then left in this state for several seconds in order to obtain an equilibrium state of director profile and ionic distribution.

3. Results

3.1. *Reset in relaxed direction*

Initially we consider the case when the applied reset pulse is in the same direction as the current relaxed state, and is to be followed by a small partial switching pulse. This would occur in a practical device if a given pixel had previously been switched in the direction of the chosen reset. In this case, an ionic field is naturally present which stabilizes the current state. This exists because ions in the ferroelectric liquid crystal material drift in response to the field set up by the spontaneous polarization. The result is an ionic field perpendicular to the cell surfaces, in the same direction as the net spontaneous polarization in the relaxed state. Normally this field hinders attempts to switch the device towards the opposite state, and, if sufficiently large, can lead to a bounce switching effect where a device switches back to the previous state after removal of a switching pulse. This is significant in materials with a large spontaneous polarization and correspondingly large ionic stabilizing field.

Now if a reset pulse is applied in the same direction as the relaxed state, before the switching pulse is applied, the ionic stabilizing field is decreased. This is because the ions drift in response to the external field, which is in the opposite direction to the field due to the spontaneous polarization. This decrease in stabilizing field leads to easier switching, with larger switched areas occurring for a given subsequent switching pulse in the partial switching regime. In the extreme of a very large amplitude (or long duration) reset pulse, the device can switch in response to the redistributed ionic field without the subsequent application of a switching pulse, as is used in our global reset scheme discussed above in § 2.

If in addition we consider the elastic effects present, then the situation becomes a little more complex. In the above discussion, the delay between the reset and switching pulse was assumed to be sufficiently long for the director profile in the cell to have returned to its equilibrium relaxed state, leaving subsequent switching to depend only on the ionic (and external field) influences. Now this may not always be the case in a real device, where for some pixels at least the switching pulse may be very close in time to the reset pulse. In this case, the elastic effects will be important. During the reset pulse, the ferroelectric liquid crystal director profile moves into a stressed state, or at least towards a stressed state, in the currently switched direction. After the end of the reset pulse, this relaxes back towards the relaxed reset state with a certain time constant (of the order of ms). If the switching pulse is applied before the relaxation is complete we would expect it to be more difficult to switch the device towards the opposite state. The ionic effects will of course still be present, so there should be competition between the elastic effects (working against the subsequent switching) and the ionic effects which help subsequent switching. As the ionic distribution will also relax after the reset, but with a much longer time constant than the elastic stress, we would expect a point of easiest switching at around the time the elastic stresses have totally relaxed.

This is investigated experimentally by varying the delay between a reset pulse and switching pulse applied to a device, and observing the device some time after the switching pulse. Data are extracted in terms of switched areas as a function of reset pulse amplitude, as discussed above. The results are illustrated in figure 1. This shows the effects expected, with an increase in switched area due to increasing reset induced ionic fields when there is a reasonable delay between the reset and switching pulses (~ 10 ms), as noted above, which is suppressed by elastic effects when there is no delay between the pulses.

3.2. *Reset opposite to relaxed direction*

When the reset pulse is in the opposite direction to that to which the cell has previously been switched, the expected results are slightly different. Again the relaxed state has a stabilizing ionic field, but this is now in the direction towards which the device will be switched after being reset. Thus the ionic field will now be expected to help our final switching pulse, leading to larger switched areas. The reset pulse will again increase the ionic field so as to enhance the final switching. Therefore in this case the effect of the ionic stabilizing field and reset pulse enhanced ionic field both add to the field in the switching direction and the same partial switching pulses applied in § 3.1 will now result in larger areas switched.

However, if we consider the variation in final switched state with variation in reset pulse amplitude, the trend will be different to that observed above. As the reset will now be switching the device away from its previous state (above it was switching towards it), small resets will exhibit a different behaviour. Clearly, below a certain reset

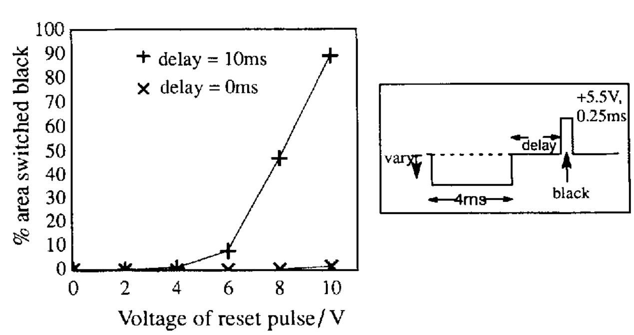

Figure 1. Plot of area switched black as the amplitude of the (white) reset pulse is increased with the device starting in the relaxed white state. Plots are shown for 0 ms and 10 ms reset to switching pulse delay times, as indicated in the inset. Data were taken after equilibrium had been reached.

pulse amplitude, the device will not be reset in the sense of being fully switched to the opposite state. The result will be a partial reset, with a partially switched domain structure. Thus we expect that with small reset pulses there will be a decrease in final switched area, as the reset will increase the area of opposite state, independent of any ionic and elastic influences. Strictly we cannot describe the device as being reset in this regime, but it will be included to complete the picture. Beyond the point of total reset we expect the ionic field to take over, and for the switched area to increase.

Again we can consider the expected effect of elastic stress in the device. As the reset is in the opposite direction to the final switching pulse, this will be expected to suppress the switched area. As the delay between reset and switching pulse is varied, the strength of this effect will also again be expected to vary. Thus for delays less than the elastic relaxation time (~ 2 ms), the combination of effects (ionic and elastic) should now lead to a decrease in switched area as the reset amplitude is increased (dominance of elastic effects), followed at larger reset amplitudes by an increase due to the ionic field enhancement.

Results for experimental studies of this nature are shown in figure 2. Final switched areas are shown for three delays between the reset and switching pulse, with variation in the reset pulse amplitude. There are three regions of interest in this, labelled as (1), (2) and (3) in the figure. In region (1) the reset pulse is insufficient to cause a complete reset of the device. This is determined by timing the flash lamp etc. in the microscope to take an image after the reset pulse has been applied (in fact just before the application of the switching pulse). For this sample, with the chosen reset pulse duration, these images indicate that for reset pulses below 3 V in amplitude, the

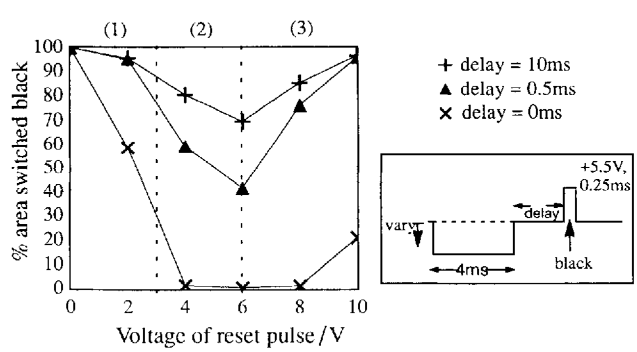

Figure 2. Plot of area switched black for variation of the (white) reset pulse amplitude with the device starting in the relaxed black state. Plots are shown for three different reset to switching pulse delay times. The deep switched area depression caused by elastic stresses following the reset pulse is very evident when there is no delay between the pulses. (1), (2) and (3) are referred to in the text.

device remains in a multiple domain state. Beyond this point the images show the device to be completely reset. Thus we see for incomplete resets (below 3 V) that increasing reset amplitude leads to decreasing final switched area, as expected. In region (2), complete reset has occurred but the final switched area continues to decrease with increasing reset amplitude. This appears to indicate that elastic stress effects are influencing the final switched area. Finally in region (3), the reset pulse enhances the ionic field sufficiently for this to increase the final switched area.

These results are as expected for the zero and 0·5 ms delays and show that, for very small delays, the elastic stress present at the time the switching pulse is applied has a significant effect on the final switched area. However, what is not expected is that even with a 10 ms delay between reset and switching pulse, the final switched area continues to decrease after a total reset has been achieved (i.e. in the range 3–6 V). It is clear from images taken between the reset and switching pulses that, on this time-scale, all of the bulk elastic stress caused during reset has relaxed. Thus there is clearly a region over which our above explanation of the elastic and ionic processes taking place is not adequate to describe fully the switching processes.

In order to examine the reset and determine whether there are any additional changes taking place for the larger resets, we also examine the transmission of a device directly. This is useful because the stroboscopic microscope cannot be sufficiently well calibrated for accurate transmission measurements, and therefore it is difficult to be certain that no further elastic changes take place for resets in the 3–6 V range. In this experiment, the device is placed between crossed polarizers and is illuminated with a 670 nm laser diode. The transmission is measured with a silicon photodiode. This is recorded on a digital storage oscilloscope during the addressing sequence and can be transferred to a computer for analysis. The results with 3 V and 5 V reset amplitudes are shown in figure 3. These are quite interesting and further illustrate a number of points discussed above. The device is initially in the relaxed black state and a 4 ms duration white reset pulse is applied at $t = 1$ ms. Both the 3 V and 5 V pulses are sufficient to reset the device fully to the white state. After the reset pulse is a 2 ms delay (before switching pulse application) during which the stressed white state in the device relaxes. It can be seen in figure 3 that, when the reset pulse is of 5 V amplitude, the device apparently relaxes further than when the reset pulse is of 3 V amplitude. This is due to the presence of a greater ionic reversal field with the 5 V reset than with the 3 V reset. From our earlier arguments, we would expect this to lead to a greater switched area (i.e. continued reversal towards black) for the 5 V reset case when the switching pulse is applied. The opposite is

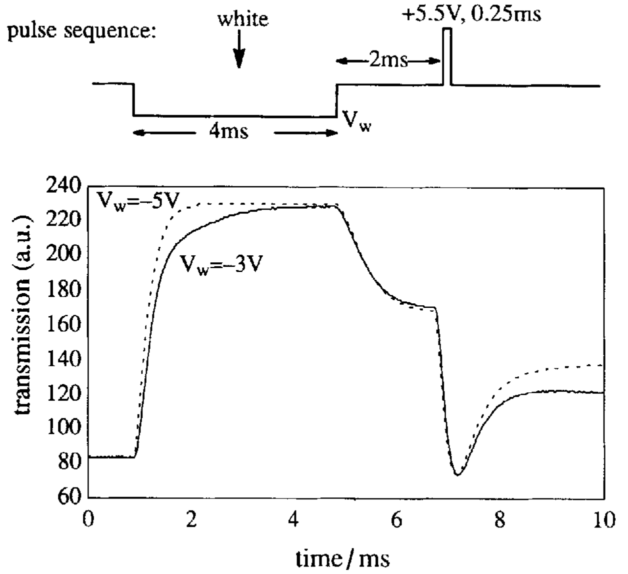

Figure 3 Plot of transmission through a device place between crossed polarizers where it is addressed with the same pulse sequence illustrated in figure 2. It is clear that just before the switching pulse, the 5 V reset case has relaxed further than the 3 V reset case; nevertheless the 5 V reset case still has less final switched area (seen evolving over 8 to 10 ms), indicating some subtle elastic stabilization which is not evident in the transmission data.

however seen to be the case, as was noted for the 3–6 V reset regime in figure 2. Thus there still appears to be some anomaly, as although the ionic field clearly causes further relaxation for the 5 V reset case, less area is ultimately switched.

In order to explain this anomaly we suggest a surface switching effect. This takes place on application of pulses with either higher voltages and/or longer times (as variation of the duration of the 5 V reset pulse also leads to the anomalous effects observed above), with longer resets leading to less final switched area, even though the ionic field is further enhanced. However, a careful study of the region over which this occurs (from $t = 2$ ms to $t = 5$ ms in figure 3), shows no further evolution in device transmission. Thus we have a situation where some further changes are clearly taking place (as evidenced in the final switched area measurements), but they are too subtle to be observed directly in transmission measurements. It is however possible that when the device is in the stressed reset state and no further change apparently takes place, some surface movement occurs. This may not be observed, because in the stressed state the reorientation from the bulk to the surface alignment is squeezed into a thin region near the surfaces of the device which does not influence the transmission greatly if it is much less than the wavelength of light in thickness. However, when subsequent switching takes place, this extra surface movement in the

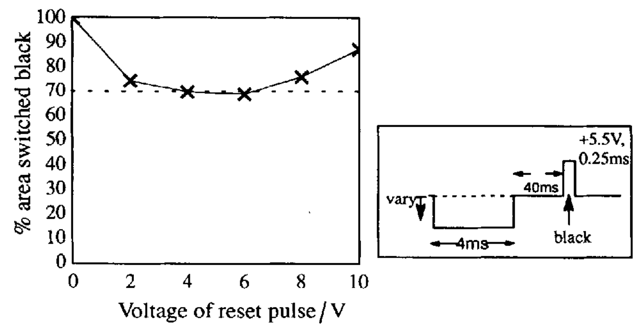

Figure 4. Plot of switched area for variation in the reset pulse amplitude when the delay between pulses is 40 ms. The region from 3 V to 6 V has now effectively flattened out.

direction of the reset state will clearly work against the switching pulse. As surface orientation is quite important in domain evolution, a decrease in the final switched area is likely to be observed. Thus even with delays between the reset and switching pulses which are long enough to allow the reset stressed state to relax, increasing the reset amplitude can still enhance the stability of the reset state.

If we accept there is a surface switching effect (which is yet to be proved), all of the switching regions observed in figure 2 can be explained. When the reset pulse to switching pulse delay is further increased (beyond 10 ms), the two regions between 3 V and 10 V in the switched area curves both flatten out indicating that the ionic enhancement effects have begun to decay *and* there are no longer elastic stability differences in the formerly anomalous region (2). This is shown in figure 4, where the delay between pulses is 40 ms. It should be noted that now the 3 V reset pulse amplitude case has decreased in final switching area to a point where switching in the 3–6 V reset regime always results in similar final switched areas. This is interesting and indicates that the additional surface switching, which we have invoked to explain the trend in region (2) of figure 2, may also take place if the device is in the relaxed reset state for a reasonable amount of time. *Thus the reset state is seen to be stabilized by either being held in the stressed state for a few ms or in the relaxed state for a few 10's of ms.*

3.3. *Suppression of reset elastic effects*

Given the problems with the influence of resets and previous elastic stressed states on switching, it is interesting to consider whether the effects can be removed with further compensating reset pulses before the switching pulse is applied. In order to consider this, we will study the switched area of a device when two resets are used before the application of the switching pulse. The first of the reset pulses will be varied in amplitude in a similar way to those above, and the second will be a fixed amplitude pulse which it is hoped will eliminate at least some of the varying effects from the first. Provided the second reset pulse is sufficient to reset the device from any previous state, we would expect *only the ionic effects to persist and not the elastic ones*. The switching pulse will always be following a well-defined total reset pulse in this case and we would therefore expect the elastic starting state to be always the same. The state of the ionic distribution and corresponding ionic field immediately before the switching pulse will depend on both the original pre-reset state and the two reset pulses.

The pulse sequence used here consists of a 4 ms long reset pulse which is varied in amplitude (as before), followed by a 1 ms delay. This is then followed by a 0·25 ms duration 10 V reset pulse which is sufficient to place the device into a total reset state whatever the state immediately preceding it. There is then a further 1 ms delay before the application of the partial switching pulse, which is chosen to switch a reasonable area of the device. The switched area is then determined as before a few hundred ms after the sequence has been applied. Because of the double reset application, we can now consider the case where the first reset is in either direction relative to the final switching pulse. Therefore the first reset pulse should decrease the final switched area when it is in the same direction as the final switching pulse (due to ionic redistribution), and similarly increase the switched area when it is in the opposite direction to the final switching pulse. In both cases, the second reset pulse will be in a fixed direction which will be opposite to the final switching pulse.

Results for this are shown in figure 5 where the initial state of the device is relaxed white and we are looking at final switching towards the white state. Remember the device is being totally reset to the black state by the second reset pulse. Considering first the case where the first reset pulse is negative (i.e. in the white direction), we see the expected decrease in final switched area as discussed above. This shows that the white reset is decreasing the white stabilizing ionic field. However, when the reset pulse is in the black direction, we also see a decrease in the final switched area for the range of reset amplitudes between 0 V and 4 V. This is similar to the effect observed earlier, but is not consistent with our above arguments, where we suggested that the second reset pulse would suppress elastic effects, leaving only the enhancing ionic contribution from the first reset pulse. It could however be argued that in this case, with both resets in the same direction, we would expect there to be a range over which the pulses increased the elastic stability of the black reset state before ionic effects begin to dominate at larger reset voltages.

We therefore also consider the case where the device is in the opposite starting state (i.e. relaxed black). The results for the same addressing sequence in this case are shown in figure 6 and appear in effect to be a mapping of the results seen in figure 5. In this case, when the reset is in the black direction (+ ve in this case), an ionic field is induced which enhances the final switching (as seen in figure 1). However when the first reset is in the opposite direction to the starting relaxed state, we again see an effect which cannot be explained in terms of the ionic influences only. Additionally in this case, the initial reset is in the opposite direction to the reset immediately preceding the switching pulse, so it cannot be argued that the two resets are having a combined elastic stabilizing effect. This is interesting, and shows that the elastic stabilizing effect from a reset pulse persists even if it is followed by a second total reset in the opposite direction before the switching pulse is applied. This indicates that the idea of a 'full' reset must be redefined, not only in terms of a reset to a uniform bulk elastic state (i.e. complete switching of the chevron interface), but also to include the extra stabilization of the surface switching as well (even though both states appear equivalent in transmission). However, as the extent of a reset clearly depends on the

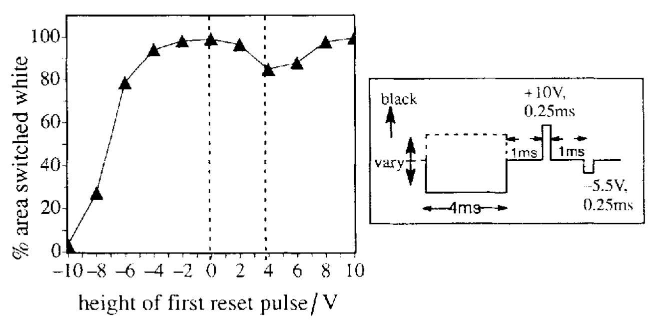

Figure 5. Plot of final switched area for a double reset system where the device is initially in the state towards which it is finally switched. The first reset pulse is varied in amplitude and the second reset pulse is fixed. There is still a region over which elastic stabilizing effects from the first pulse cause a decrease in final switched area, indicating that a second reset pulse is not sufficient to erase the effects of the first.

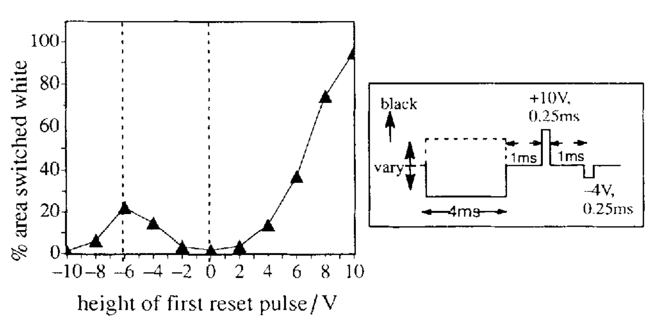

Figure 6. Final switched area with a double reset where the device is now initially in the opposite state from that towards which the final pulse will switch. The reset elastic enhancement effects are still observed.

initial state, it becomes difficult to define a particular reset pulse without knowing the state from which the reset is to occur. The implication of this is that not only ionic effects, but also elastic effects can persist beyond reset pulses, and unless more sophisticated means of eliminating these effects can be developed, knowledge of previous switched states will have to be included in device addressing schemes aimed at partial switching.

4. Conclusions

We have seen that not only ionic content, but also elastic stress has a considerable effect on switching in ferroelectric liquid crystal devices. This is particularly so in the very sensitive partial switching regime. There is an apparent anomaly in the process which does not fit in with explanations based on ionic content redistribution and bulk elastic stress. It is proposed that this is due to some surface switching which is insufficient to have a measurable influence on device transmission during switching, but is sufficient to have a small effect on the final partially switched areas. The results over a range of reset and switching pulses for both starting states are consistent with this explanation. We also have shown that these effects persist even if a pair of reset pulses is used, where the second is of fixed amplitude and duration, but the first is varied. Thus neither the ionic nor elastic effects are easy to erase.

Clearly the results obtained here raise some issues in the design of drive schemes for ferroelectric liquid crystal devices. In any device with an addressing scheme which consists of a reset pulse followed some time later by a switching pulse, the effects we have discussed will be important. Assuming a video rate type of display with whole frame resets, a situation would exist where, after a reset pulse, various points in the display would be addressed over the next 20 ms with delays from the reset pulse. As this is the very time-scale on which we observe the interactions between ionic and elastic stress effects, it will be difficult to design a scheme which works well unless these influences are considered.

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