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# Importance of Ion Transport in Industrial LCD Applications

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# Importance of Ion Transport in Industrial LCD Applications

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Ion transport in liquid crystals can have a negative influence on liquid crystal display performance. We introduce the importance of ion transport in industry and and the performed research. Afterwards the contribution of University of Gent will be presented in three topics: determination of concentration and mobility of ion species; influence on image sticking; role in asymmetric (reflective) cells.

*Keywords:* Liquid Crystals; ion transport

## 1. INTRODUCTION

Liquid Crystal Displays have deeply penetrated the display market during the last twenty years and its importance and applications continuously grow. This goes from small consumer products to large area displays, projection and virtual reality applications.[1] With increasing display performance requirements, problems with ion transport become more important. The presence of ions in liquid crystals requires a completely symmetrical addressing of the liquid crystal. This leads to more complicated driving schemes[2], a careful design of the switching device[3] and the presence of storage capacitors[4] which increase the needed maximum current of the TFT[5].

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A more recent hot topic is the ion transport in cells with an asymmetric behaviour such as reflective microdisplays used for applications in virtual reality, projection and small pocket displays[19].

Ion transport has been studied by several groups for many years[6-8]. These studies give a theoretical description of the time evolution of ion distributions in addressed LCDs. The influence of the ions on the electrooptical characteristics is experimentally determined and confirmed by detailed simulations. In most cases the impedance of a cell is measured as a function of frequency and related to the ionic content. Our research group made its own contributions in the fields of theory[9], measurements[10] and simulations[11]. Unlike the others, we put a strong emphasis on direct drive methods and are able to investigate the current directly caused by ionic movements in one-pixel test cells. In this article we will focus on the acquired knowledge (the measurement of the ion content,§3) and two more recent themes (image sticking,§4 and reflective cells,§5). A short conclusion summarises the state of the art and the future challenges.

## 2. STUDY OF ION TRANSPORT

Ion transport has a complicated behaviour and influence in liquid crystal displays. Its charge transport is coupled to the electric field distribution in the l.c., and therefore to the orientation of the l.c. director and thus to the optical transmission or reflectance. When a charge is put on the pixel (Active Matrix), the ions will move to the side and decrease the voltage across the pixels causing a time dependant voltage and transmission. The electrooptical performance is now a function of the frequency and thickness of the display since the time scale of the influence of ion transport is of the order of the ions' transit time. The charge transport equation contains a drift and a diffusion term that depend on the ion concentration and its gradient[12]. Its solution is influenced by boundary conditions at the alignment layers that express surface trapping and release.

An exact simulation program[13] is feasible but requires much computer time, especially because of the large concentration gradients at the boundaries. We consider special cases where the interpretation is as easy as possible.

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## 3. MEASUREMENT OF ION CONTENT.

We have set up a measurement system that allows easy determination of ion transport parameters[13,14]. First we realise a rest state where the ions are uniformly distributed throughout the liquid crystal. In (symmetric) nematic liquid crystal this is realised by short circuiting the liquid crystal during a few seconds, but in e.g. ferroelectric liquid crystals we must add a d-c bias in order to compensate the field caused by the permanent polarisation. We then apply a square wave voltage of 100 Hz or slower and measure the current. The current during the first pulse is called the transient current, during the second and third pulse respectively the negative and positive regime current. We make sure that the following two conditions are fulfilled : we work below the threshold voltage so that no reorientation of the molecules takes place; secondly, the ion concentration is sufficiently low so that it cannot drastically influence the electric field distribution during the ion movement through the l.c. This is usually expressed by the so-called "space charge limit" : the total ion charge and when put on one of the electrodes (the opposite charge on the other electrode) should charge the capacitance $\varepsilon.\varepsilon_0/d$ to the applied voltage V i.e. $qn_{scl}d = \varepsilon.\varepsilon_0 V/d$. For $\varepsilon$=3,5, d=10μm, V=1V, the space charge limit is $n_{scl} = 2.10^{18}$ $m^{-3}$

Under these conditions the transient current shows a linear decrease (FIGURE 1). From the transit time one can deduce the ion mobility by $\mu=d^2/Vt_{tr}$ and from the peak current one can deduce the

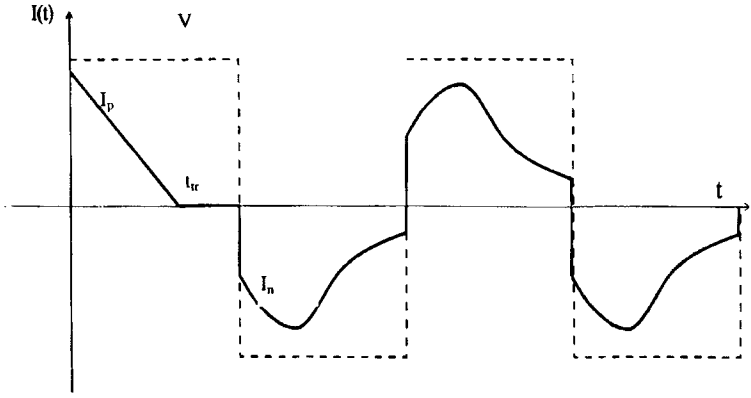


FIGURE 1 Transient and regime currents (1 ion species).

concentration by $n=I_p t_{tr}/qd$. The regime currents show a bump caused by the slow release of ions trapped at the surface; the relation between the shape of the regime current curves and the transport characteristics is not so simple anymore. If there are more ion species with different concentrations and mobilities the transient current becomes piecemeal linear. We succeeded in specifying up to three ion species with different mobilities.

In co-operation with l.c. manufacturers we have been able to detect the very low ion concentrations of modern l.c.-mixtures. We have tried to model mobility to the motion of a sphere in a viscous fluid, but the apparent radius of the sphere was up to two orders of magnitude larger than expected. This has two standard explanations : the ions are surrounded by water molecules and we should use the unknown microscopic viscosity instead of the known macroscopic viscosity. Measurements at different temperatures allowed the determination of activation energies and control of the measurement accuracy. We measured concentration from the very low values of $10^{17}$ $m^{-3}$ up to high concentrations of $10^{20}$ $m^{-3}$ in artificially doped mixtures and in ferroelectric and antiferroelectric mixtures. Mobilities are of the order of $10^{-9}$ $m^2/Vs$ to $10^{-11}$ $m^2/Vs$. The high concentrations of course require a matching process of measurement and simulation.

## 4. IMAGE STICKING.

This is the phenomenon that images that appeared for a long time remain visible minutes after shut off. It is generally accepted that this is caused by ions that are stuck at the interface l.c.-alignment layer, due to a dc electric field present in the addressing signals. If 1% of the transmission of the original image remains in a display, it can be detected.

In single pixel prototypes, as we use in our measurements, changes in transmission of 1% can hardly be detected. In any case the transmission is not a good tool to investigate the ion sticking phenomenon. However the influence of ions that are stuck at the l.c.-alignment layer interface on the transient and regime current profiles is much stronger. We have therefore set up a measurement system[15] that applies a dc stressing between 0.2 to 0.5 Volt during 5 hours, every 10 minutes interrupted for a measurement cycle. This cycle consists of a 2 second short circuit, a 1 Volt square wave of a transient pulse and three

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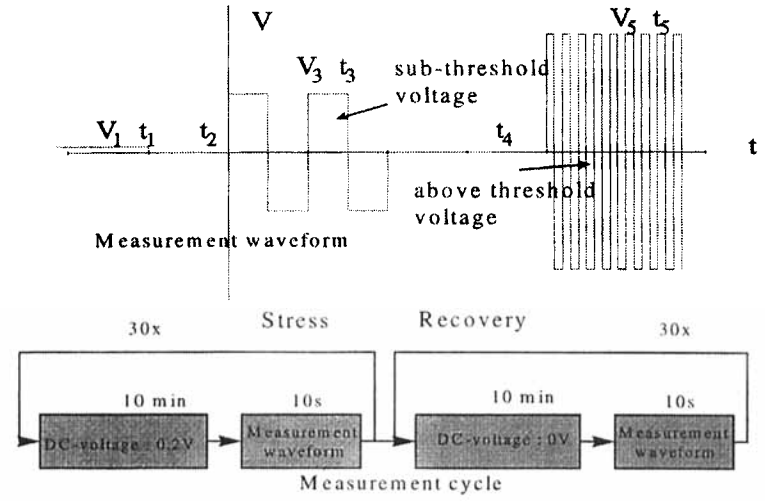


FIGURE 2 Measurement cycle and stress and recovery periods.

regime pulses of 100 MSc (10 Hz), and then a 100 Hz above threshold square wave to measure the transmission. This was followed by a 5 hour recovery period using the same interruptions for measurements. This is shown in FIGURE 2.

In order to interpret the results, we make a distinction between "fast" and "slow" ions. Fast ions are sufficiently mobile so that their travel through the l.c. can be detected by the current profiles. Slow ions may have large concentrations but they are too slow to be detected in the current profiles. We also make a distinction between ions being "trapped" at the interface and being "stuck" at the interface. The trapped ions have a short release constant and are the cause of the bumps in the regime currents. The ions that are stuck have a much longer release constant, of the order of hours. These ions are responsible for the image sticking effect. We have no information nor insight in the physical nature of this sticking phenomenon : is it a chemical reaction or is it the presence of very deep traps ?

If the dc stressing voltage, say 0.4 Volt, is applied the ions move to one side and build up an opposite field. The part of the applied voltage over the l.c. is decreased. In the configuration of FIGURE 3 (the negative ions are ignored), we have

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$$V_{lc} = \frac{C_t V}{C_{lc}} - \frac{Q_i}{C_1} \cdot \frac{C_t}{C_{lc}} \tag{1}$$

where $C_1$, $C_{lc}$ and $C_t$ are the unit area capacitances of the alignment layer, of the l.c. and of the cell respectively. In order to estimate order of magnitudes, we may assume the ε of the l.c. and of the alignment layers to be equal (=5) and we obtain

$$V_{lc} = \frac{d_{lc}}{d_t}(V - \frac{Q_i}{C_1}) \approx V - \frac{Q_i}{C_1}$$

The charge required to destroy 0.4 V is $Q_i = C_1 V = q n d_{lc}$ and corresponds to a homogeneous ion concentration of about $10^{+19} m^{-3}$. Normally the ion concentration will be much less, so that the d-c stressing field is only partially destroyed. Part of the charge $Q_i$ is deeply trapped ("stuck"). The other part will be released during the measurement cycle. Since the concentration $n = 10^{19} m^{-3}$ is far above the space charge limit, it still means that if this charge, or even part of it, starts moving over the l.c., it can drastically influence the electric field distribution in the l.c. Notice that the influence of $Q_i$ on $V_{lc}$ is minimum if $Q_i$ is in the middle of the l.c., but the disturbance of the electric field distribution is maximal.

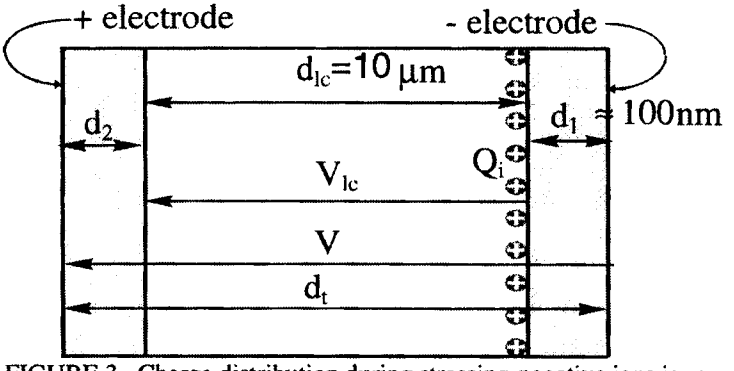


FIGURE 3 Charge distribution during stressing-negative ions ignored.

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The current profiles show the following characteristics. During the stress period the transient profile gradually builds up a bump just as in the regime profiles. This is explained by the fact that the short circuit period no longer guarantees a homogeneous distribution. The charge of the ions that are "stuck" to the interface ($Q_i$) gradually increases, the counterfield produced by these charges also, and thus the mobile ions that are "trapped" at the positive electrode during the short circuit period also. At the transient period they are released. During the recovery period, the short circuit period gradually resumes its normal role, i.e. causing a homogeneous distribution. As the counterfield gradually builds up during the stress period, an asymmetry shows itself during the current measurements: at the transient pulse and the third (positive) pulse the counterfield works against the applied field, and at the second and fourth pulse (negative pulses) the counterfield enhances the applied field, and causes a somewhat larger current profile. Also the integral of the current profile (the so called current moment, in fact the total distance travelled by the mobile charges) shows this asymmetry.[16,17]

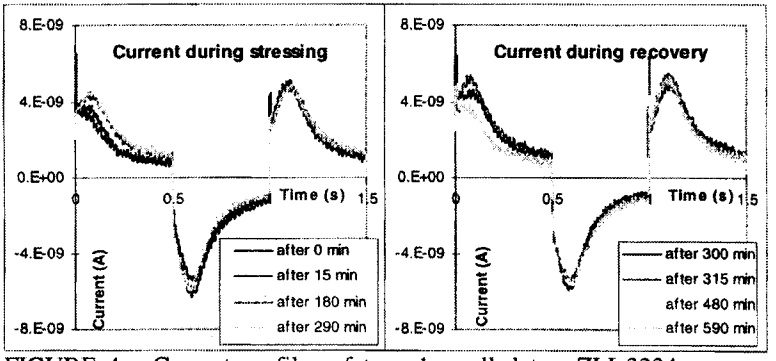


FIGURE 4 Current profiles of type 1 : cell data : ZLI 3224, $n_1=n_2=1.08\ 10^{18}$, $\mu_1=1.6\ 10^{10}$, $\mu_2=3.1\ 10^{-11}$, $n_3=3.5\ 10^{18}$, $\mu_3=4.3\ 10^{-12}$.

In the measured cells, we found two types of cells with a drastic difference. In the first type (FIGURE 4) the current profiles did not drastically change during the stress period (apart from the transient bump and the asymmetry). That means that the number of ions participating in the travel back and forth through the l.c., stays

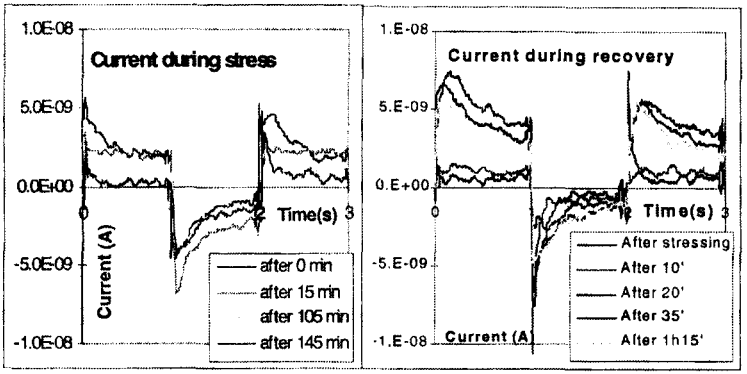


FIGURE 5 Current profiles of type 2 : cell data : ZLI 4757, $n_1$=1.28 $10^{18}$, $\mu_1$=1.2 $10^{-10}$, $n_2$=7.36 $10^{18}$, $\mu_2$=1.28 $10^{-11}$.

approximately the same. The ions that are "stuck" must thus belong to the so called "slow" ions i.e. ions that are present but are so slow that their motion cannot be detected in the current profiles. In the second type (FIGURE 5) the current systematically decreases during the stress period. This means that the ions that are "stuck" are (at least partially) so called "fast" ions i.e. ions that originally participate in the travel back and forth, and gradually become stuck during the stress period. In both cases the cells get back to their initial state during the recovery period. We are still trying to correlate the two types of cells to physical differences between the cells.

## 5. ASYMMETRIC CELLS.

Reflective cells are used in high performant microdisplays for niche applications[18,19]. They have two different electrodes, A transparent one (ITO) and a reflective one (e.g. Al). Experiments show a different reflection for positive and negative applied voltages. From private communications[20] we know that this is caused by the difference in work function of the electrodes $q\Delta\phi=q(\phi_I-\phi_a)$ (FIGURE 6).

If the ε of the l.c. and the alignment layers are the same, and if they are perfect insulators (no charges), the electric field in the l.c. caused by the applied voltage and the difference in work function is

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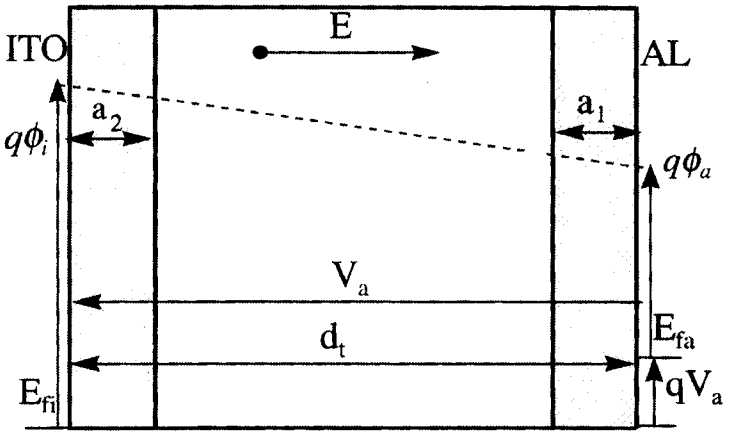


FIGURE 6 Influence of work function difference.

$$Ed_t = V_a - \Delta\varphi \quad , \quad \Delta\varphi = \varphi_i - \varphi_a \tag{2}$$

This built in electric field is not caused by ionic charges in the l.c. or in the alignment layers, but by electrons at the surface of the electrodes that are in thermal equilibrium with the electrodes.

Other causes of built-in fields can come from charges in the alignment layers. If e.g. there is a charge separation in the alignment layer $a_1$, the charge at the electrode has no influence on the voltage over the l.c., but the charge at the interface l.c.-alignment layer has an influence as calculated in Equation (1). If we think of a negative charge $Q_i$, we thus obtain for the voltage across the l.c. :

$$V_{lc} = \frac{C_t}{C_{lc}}(V_a - \Delta\Phi + \frac{|Q_i|}{C_1}) \tag{3}$$

Both the effect of the work function difference and of the charge at the lc-alignment layer interface is the same : they cause a built-in field of the same nature as discussed in section 3, only the built-in field may be a lot larger. In section 3, we have shown how to discuss and interpret the consequences of such built-in fields.

The built-in field caused by the work function difference is the primary cause of trouble and disturbances in asymmetric cells. Various

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companies are following their own way of thinking to find a solution to this problem.

## 6. CONCLUSION

In this paper we showed the short state of the art of the characterisation of ion transport as well as the different new topics involved in it. Our measurement technique of the ion content (§3) is used by several companies (Philips, Merck, ...) and gets a lot of interest from many others. This assessed knowledge has been expanded to the terrain of ferroelectric and antiferroelectric liquid crystals[21]. The physical origin of image sticking is still unknown, but universities[22] and industries[23,24] are focusing on measuring and simulating the phenomenon and reducing its effect by clever addressing techniques. Ion transport in Reflective Displays is becoming very important for microdisplay applications. Further results on this topic will be published in due time.

## 7. ACKNOWLEDGEMENT

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