

This article was downloaded by:

On: 26 January 2011

Access details: *Access Details: Free Access*

Publisher *Taylor & Francis*

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



## Liquid Crystals

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713926090>

### Transient leakage current in nematic LCDs

B. Maximus<sup>a</sup>; C. Colpaert<sup>a</sup>; A. de Meyere<sup>a</sup>; H. Pauwels<sup>a</sup>; H. J. Plach<sup>b</sup>

<sup>a</sup> Laboratory of Electronics, University of Ghent, Ghent, Belgium <sup>b</sup> E. Merck, Industrial Chemicals Division, Darmstadt, Germany

**To cite this Article** Maximus, B. , Colpaert, C. , de Meyere, A. , Pauwels, H. and Plach, H. J.(1993) 'Transient leakage current in nematic LCDs', *Liquid Crystals*, 15: 6, 871 – 882

**To link to this Article:** DOI: 10.1080/02678299308036506

**URL:** <http://dx.doi.org/10.1080/02678299308036506>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

## Transient leakage current in nematic LCDs

by B. MAXIMUS\*, C. COLPAERT, A. DE MEYERE  
and H. PAUWELS

Laboratory of Electronics, University of Ghent, Sint-Pietersnieuwstraat 41,  
B-9000 Gent, Belgium

and H. J. PLACH

E. Merck, Industrial Chemicals Division, Frankfurter Strasse 250,  
D6100 Darmstadt, Germany

(Received 4 January 1993; accepted 25 July 1993)

In this paper we present the transient leakage current measurement method for nematic liquid crystal displays as a technique to obtain information on the mobility and concentration of ionic impurities. The mobility depends on the temperature according to an Arrhenius-type relation, with an activation energy of about 0.3 eV. This dependence can be explained through the variation of the LC viscosity with temperature. The transported charge has also an Arrhenius relation, with an activation energy around 0.2 eV. Additionally, the influence of both a heat treatment and UV illumination on these parameters was investigated.

### 1. Introduction

One of the most important parameters of liquid crystals (LCs) is their resistivity, because a low resistivity can limit the success of most applications. For example, in AM-TN LCDs too high a conduction means that the charge on the pixel is not sufficiently retained. This largely affects the number of grey scales that can be used. It becomes important, especially for operation at elevated temperatures and can even limit the upper operating temperature [1-4]. Also in SSFLCDs, charges can accumulate in the neighbourhood of the electrodes and in this manner the bistability—the most important feature of those displays—can be destroyed [5, 6].

Some recent studies have tried to get a better understanding of the conduction mechanism in LCDs. This conduction is caused by the presence of ionic impurities in the LC cell, so the general idea is to investigate the concentration of ions and their motion in an electric field. A common technique to do so is by studying the leakage current when a square voltage wave is applied [7-12]. In the present paper we concentrate on the first period of the applied square wave voltage and study the transient current behaviour. This seems to be an easy way to determine the mobility and the density of the impurity ions, since a simple model is capable of explaining the current behaviour. Unfortunately some restrictions have to be imposed; for example, only sub-threshold voltages can be used, and the results are only valid if the ionic concentration is rather low. Using this method we can then examine the influence of higher temperatures or UV illumination on the density and mobility of the ions and on the resistivity of the mixtures in general.

\* Author for correspondence.

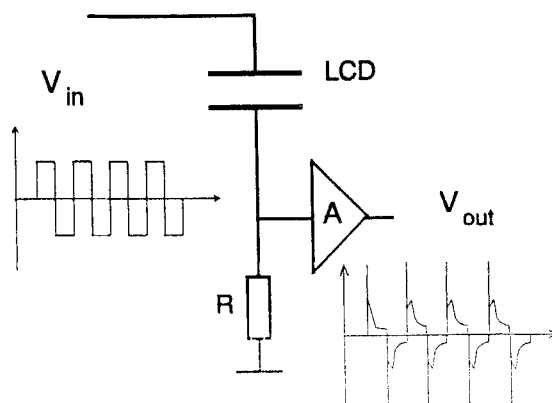


Figure 1. Measurement set-up.

## 2. Measurement method

### 2.1. Set-up

The transient leakage currents are measured with the set-up shown in figure 1. A burst of a square voltage wave ( $f = 1\text{--}20$  Hz), with a small number of periods (usually 4) is applied to the cells. Between these bursts we wait at least 5 min for equilibrium in the cell to be re-established. The current flowing through the cell is measured by means of a sensor resistor. Use of voltages below those required for the Fréedericksz transition is recommended. Above this threshold, the cell starts to switch and the changing capacity causes a disturbing supplementary current. When the voltages are sub-threshold, the pixel capacity remains constant and the only small nuisance we have relates to the charging current of the pixel capacitor each time the voltage is altered, but this effect quickly vanishes.

The whole set up is placed in a temperature controlled environment, allowing measurements at temperatures between  $20^\circ\text{C}$  and  $100^\circ\text{C}$ .

### 2.2. LCs

TN LCDs were prepared with different LC materials from Merck, all containing cyano-compounds. The LC layer thickness is always  $d_{\text{LC}} = 8 \mu\text{m}$  and the pixel surface is  $S_{\text{pix}} = 4.5 \text{ cm}^2$ . In table 1, some data can be found for the three different LCs and the voltages that were used in the experiments. There are two high-threshold mixtures and one classical TFT mixture ZLI 3224. The test cells were fabricated at our laboratory in Gent [4]. In this process we used Baltracon Z20 glass substrates from Balzers covered

Table 1. Some data on the LCs used:  $\epsilon_{\perp}$  and  $\epsilon_{\parallel}$  are the dielectric permittivities of the LCs determined perpendicular and parallel to the director. The average dielectric permittivity is  $\bar{\epsilon} = \frac{1}{3}(\epsilon_{\parallel} + 2\epsilon_{\perp})$ .  $\rho_{20}$  and  $\rho_{60}$  are the bulk resistivities at  $20^\circ\text{C}$  and  $60^\circ\text{C}$  respectively.  $V_{10}$  is the electro-optical threshold in TN cells with a retardation of  $0.5 \mu\text{m}$ .  $V_a$  is the amplitude of the square wave voltage applied.

LC Data								
LC	$\epsilon_{\perp}$	$\epsilon_{\parallel}$	$\bar{\epsilon}$	$\rho_{20}/\Omega \text{ cm}$	$\rho_{60}/\Omega \text{ cm}$	$V_{10}/\text{V}$	$V_a/\text{V}$	
<b>A</b>	ZLI-4757	3.5	4.1	3.7	$7 \times 10^{13}$	$1 \times 10^{13}$	6.84	5.5
<b>B</b>	ZLI-4520	3.2	4.5	3.6	$4 \times 10^{13}$	$8 \times 10^{12}$	4.74	3.0
<b>C</b>	ZLI-3224	3.8	11.6	6.4	$9 \times 10^{11}$	$2 \times 10^{11}$	2.09	1.0

with an ITO layer ( $R_{\square} < 300 \Omega_{\square}$ ) and a  $\text{SiO}_2$  passivation layer. The polyimide used was AL-1254 from JSR; the seal and end seal materials were respectively Norland 91 and Vitralit 7514 UV glues.

We also used LCDs made with LC A for two other tests:

- (i) The influence of 25 h and 50 h UV illumination ( $5 \text{ mWcm}^{-2}$ ).
- (ii) The influence of a heat treatment (10 h at  $120^\circ\text{C}$ ).

2.3. Transient current

Typical transient currents are shown in figure 2. In the first half of the current, two different parts can easily be observed. First there is an almost linearly decreasing part, and then a more constant current level is obtained. In the literature this part is often called (quasi) steady state current, 'quasi' because this current is still slowly decreasing and it takes a very long time before it eventually becomes 'steady'.

The behaviour of the current for the first half of the first square wave applied is straightforward. We can expect an equilibrium state at the beginning of the

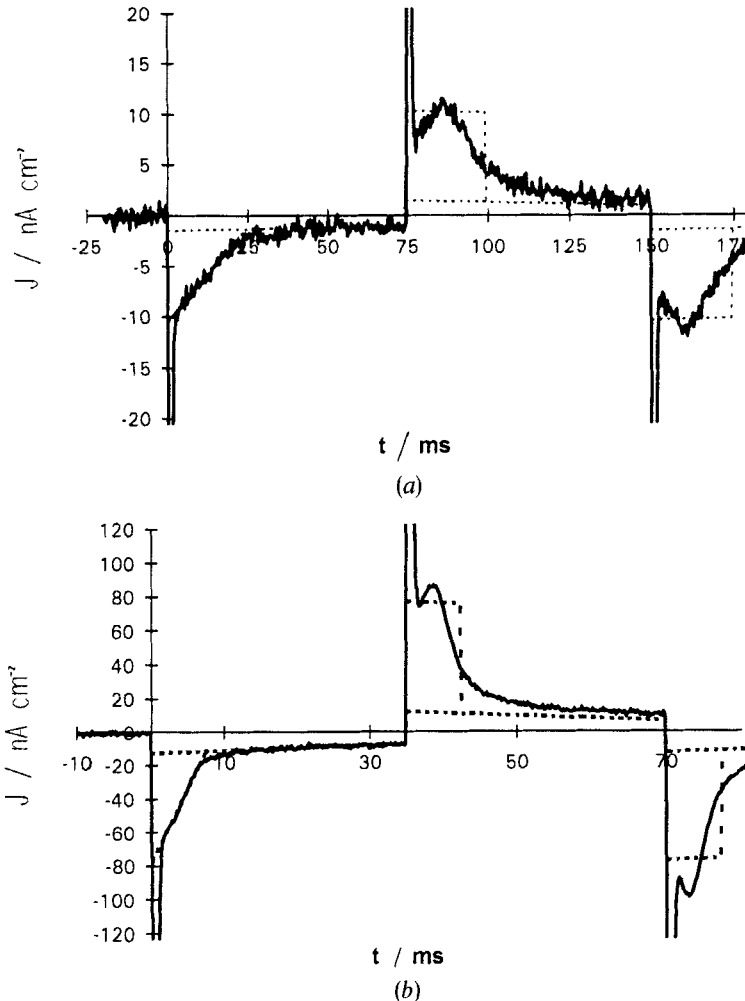


Figure 2. Typical transient current measurements (LC A after 25 h UV): (a) at  $50^\circ\text{C}$ , (b) at  $90^\circ\text{C}$ .

Downloaded At: 10:56 26 January 2011

measurement, which means that ionic species, present in the LC, are uniformly distributed over the cell. When the voltage is applied, these ions migrate towards the electrodes and we measure a linearly decreasing current. The end of this part is reached after a period equal to the ion transit time.

There are several possible explanations for the quasi steady-state part of the current:

Injection of charge through the imperfectly insulating alignment layers; with this charge new ions are formed and transported in the LC.

Another kind of DC current, for example, a surface current.

Transport of some other sort of ionic species with a non-detectable transit time (i.e. because the mobility is very small).

Dissociation of neutral impurities giving birth to new ions which in their time migrate towards the electrodes.

When the voltage is altered the ions move in the opposite direction. But now the initial condition is different (for example, all ions of one sign of charge are assembled in the neighbourhood of the same electrode), and this causes a completely different current behaviour, i.e. the observation of a maximum in the current, an effect which has already been described in other publications [7–13]. Such a curve is more complicated compared to the linear decay in the first half period. For example, the current maximum in this case does not match with the ion transit time. In fact, a more explicit model is necessary in order to understand this current behaviour fully, including assumptions about the interaction of the ions with alignment layers upon the electrodes and about the recombination and generation of ions in the bulk [8–11]. At this moment however, there is no full agreement on the exact model in the literature.

#### 2.4. Definitions

We use the first half period of the transient current and the simplifications introduced in [13], as shown in figure 3, to determine:

$t_{tr}$ : The transit time of the ions. Using  $t_{tr}$ , the mobility  $\mu$  of the ions can be calculated because  $t_{tr} = d_{LC}/\mu E = d_{LC}^2/\mu V$ .

$Q_p$ : The density of charge that is transported during the sweep out of the ions present at the start. The surface of the triangle in figure 3 is  $Q_p/2$ .

$Q_s$ : The density of charge that is transported by the (quasi) steady state current, during the transit time  $t_{tr}$ .

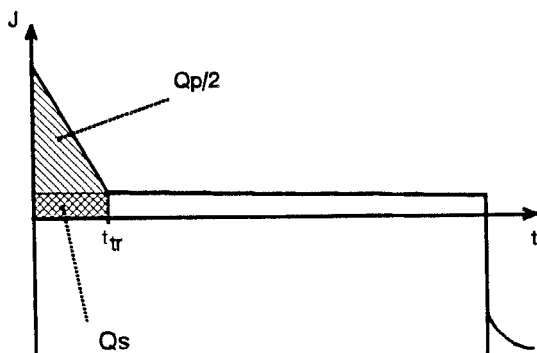


Figure 3. Definition of  $t_{tr}$ ,  $Q_p$ , and  $Q_s$ .

In the case of figure 2 we obtain:

- (a) 50°C:  $t_{tr} = 24.4 \text{ ms}$ ,  $Q_p = 2.2 \mu\text{C m}^{-2}$ ,  $Q_s = 0.31 \mu\text{C m}^{-2}$ ,
- (b) 90°C:  $t_{tr} = 7.5 \text{ ms}$ ,  $Q_p = 4.9 \mu\text{C m}^{-2}$ ,  $Q_s = 0.81 \mu\text{C m}^{-2}$ .

2.5. Restrictions: noise and space charge

Unfortunately, there are restrictions to the application of this method. In the two following paragraphs, the lower and upper limit for the detectability of the charge density  $Q_p$  are determined. Hereto, the small voltage (less than 1 per cent of  $V$ ) across the thin alignment layers (c. 50 nm) is neglected so as to keep the formulae simple. In that case,  $V$  equals the voltage across the LC layer.

- (i) As we are at present not able to average the transient curves, noise prevents the detection of current levels in the nA region. To describe the limit, formula (1) can be used

$$I_p = J_p S = \rho_p \mu E S = \frac{Q_p \mu V}{d_{LC}^2} S > 10 \text{ nA.} \tag{1}$$

Here  $Q_p$  is the charge density per  $\text{m}^2$  pixel area,  $\rho_p$  is the charge density per  $\text{m}^3$ , and  $J_p$  and  $I_p$  are the current density and the current level due to the motion of this charge.

- (ii) On the other hand the maximum admissible conduction is also limited. Indeed, if the amount of transported charge approaches the ‘space charge limited’ case  $Q_{SCL} = \epsilon_{\perp} \epsilon_0 V / d_{LC}$ , the local electrical field is disturbed by the present charge during the transport. Therefore the simple approximation  $E = V / d_{LC}$  throughout the LC layer is no longer valid, and the transient current deviates from the perfectly linear decreasing function of time. Simulations according to the model in [10] show that in this case the deviations between the ‘measured’  $\mu$ - and  $Q$ -values and the actual ones become intolerably large.

As a summary, we can state that the amount of charge in the LC layer has to be in the range given by the relation (2), in order to ensure valid results. In our case, this interval is somewhat small, but it can be increased with an improved measurement system, or through the use of a smaller  $d_{LC}$  or a higher voltage  $V$

$$\frac{I_{noise} d_{LC}^2}{\mu V S} < Q_p < \frac{\epsilon_{\perp} \epsilon_0 V}{d_{LC}}. \tag{2}$$

3. Results

3.1. Influence of voltage on mobility and transported charge

Neither the experimentally determined mobility of the ions nor the transported charge are dependent on the applied voltage (see figure 4, measurements on LC A after 25 h UV, at 70°C). Therefore, we can compare results obtained from the 3 LCs, although different voltages were used in the measurements.

3.2. Mobility

In figure 5 the mobility of the ions is plotted as a function of temperature, for the different experiments. In figure 5 (a) the results for the three different LCs are compared. In the case of the materials with high thresholds (LC A and LC B), measurements were only possible at temperatures above 80°C.

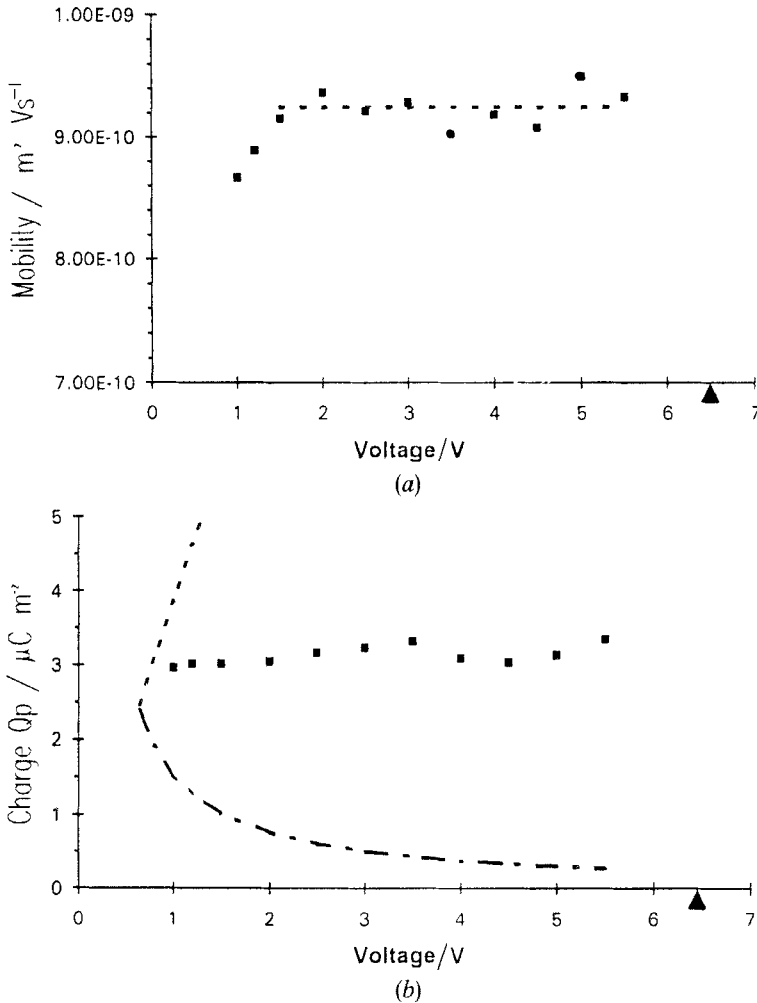


Figure 4. Influence of voltage on (a) the mobility of the ion and (b) the transported charge  $Q_p$  (lower figure) for LC A (after 25 h UV) at 70°C. In (b), the measurements are denoted by (■), the SCL limit by (---) and the noise limit by (—).

In figure 5(b) the results for cells with LC A after different pretreatments are given. Here we can give no results for the case of 50 h UV illumination, because the measured current starts to deviate from theory: there exists a small bump in the current before the linear decrease. This effect was observed with several LCDs after long enough UV illumination. The effect obstructs the determination of the transit time, not of the amount of transported charge.

There is no significant difference in the mobility of the ions in the different LCs, and there is also little influence from the UV illumination and from the heat treatment, as shown for LC A in figure 5(b).

In general it seems that the mobility of the ions follows an Arrhenius equation (3). For our data  $W$  would be around 0.3 eV.

$$\mu = A \exp\left(-\frac{W}{kT}\right). \quad (3)$$

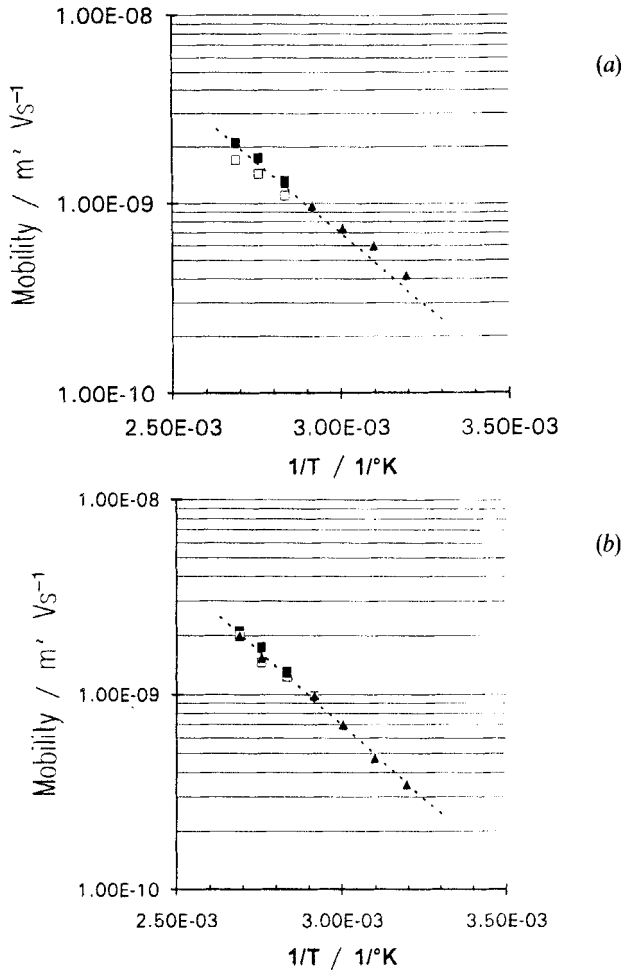


Figure 5. Mobility for different temperatures: (a) LC A, B and C, (b) influence of UV and heat treatment on LC A. In (a), LC A denoted by (■), LC B by (□) and LC C by (▲). In (b), LC A is denoted by (■), LC A, 10 h at 120°C by (□) and LC A, 25 h UV illumination by (▲). In both (a) and (b), the Arrhenius plot is shown as a dotted line.

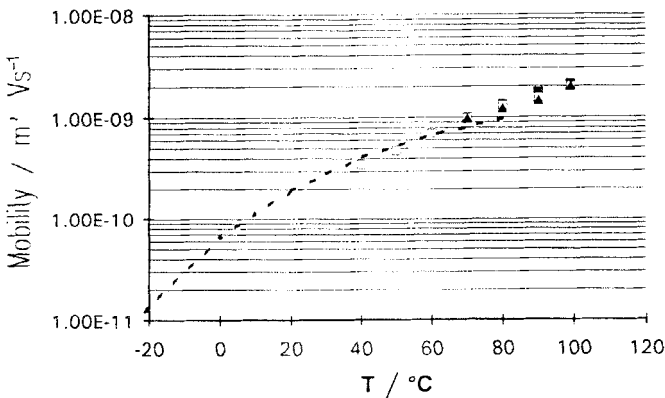


Figure 6. Comparison between the measured mobilities and a fit of the bulk viscosities to  $C \times 1/\eta$  (dashed line) for LC A.



It is our feeling that these observations need to be explained with Stokes' law (4), which states that the product of the mobility of an ion and the viscosity of the LC mixture  $\eta$  is a constant depending only on the (apparent) particle radius  $R$  and the ionic charge  $q$  [14]

$$\mu = \frac{q}{6\pi\eta R} = C \frac{1}{\eta} \quad (4)$$

To be exact, we would have to use the Miesowicz viscosity coefficient  $\eta_3$ , because the motion of the ions is perpendicular to the LC director [15].

Now, in [15] it is also shown that to a first approximation, all the Miesowicz viscosity coefficients vary as in equation (5), with 0.3 eV as a typical value for  $E$ . This would explain the value for  $W$  in (3).

$$\eta_j \approx \eta_{0,j} \exp\left(\frac{E}{kT}\right), \quad (5)$$

This theory can also be checked experimentally: it should be possible to fit a curve of  $C \times 1/\eta$  to the measured mobilities. Figure 6 shows such an attempt for LC A; the dashed line presents  $C/\eta$  when an (apparent) particle radius  $R = 20 \text{ \AA}$  is considered. However, we had to use the experimentally more accessible bulk viscosity values  $\eta_b$  instead of  $\eta_3$ , and this might explain why the fit is still rather poor.

Stokes' law also explains the rather small mobility variations of the ions in the different LCs, because these mixtures all have a comparable viscosity, and the negligible influence of UV illumination and heat treatment, because they do not change the viscosity of the LC mixture. But of course, this is only valid if  $R$  in formula 4 remains constant; therefore, in all these cases we expect the ions to have a comparable (apparent) radius.

### 3.3. Charge

In our investigations, we found  $Q_p$  and  $Q_s$  to be of similar magnitude,  $Q_s$  being slightly smaller than  $Q_p$  (table 2). Only for the sample of LC A, which was illuminated with UV,  $Q_p$  became significantly larger than  $Q_s$ . Another observation is that for each experiment,  $Q_p/Q_s$  is almost constant for different temperatures or voltages.

These observations allow us to elaborate on the physical meaning of  $Q_s$ . As has already been mentioned in § 2.3,  $Q_s$  represent the charge density that is accumulated at the electrodes during the period  $t_{tr}$ , but only due to the steady state current, further called  $I_s$ . In § 2.3 we have already described some possible explanations for  $I_s$ . Let us now investigate whether these can be reconciled with the measurements of  $Q_p$  and  $Q_s$ .

Both the assumption of a leakage current through the alignment layer and the hypothesis of a surface current suggest an increase of  $I_s$  with a higher temperature or voltage, but they do not explain the proportionality of  $Q_s$  and  $Q_p$ .

However, in the case that  $I_s$  is caused by the movement of ions with a very small mobility, one might expect a constant ratio  $Q_p/Q_s$ . Indeed, for any kind of ion, the influence of both temperature and voltage variations on the mobility and on the number of ions is more or less proportional.

When  $I_s$  is due to the generation of new ions, the temperature will not have an influence on  $Q_p/Q_s$ : while the generation process becomes more intense, the amount of ions initially present also increases. However, if the voltage is increased, theoretically we should observe a constant [13] or an unproportionally increasing

Table 2. Values for  $Q_p/Q_s$  for the different experiments. The reproducibility of the  $Q_p/Q_s$  determination is not perfect; deviations up to 10 per cent were observed when the measurements were repeated. This explains also why the two  $Q_p/Q_s$  values for LC A after 25 h UV illumination and for  $T=70^\circ\text{C}$  and  $V_a=5.5\text{ V}$  are not identical.

$Q_p/Q_s$							
$T/^\circ\text{C}$	LC A	LC B	LC C	LC A (25 h UV)	LC A (10 h 120°C)	$V_a/\text{V}$	LC A (25 h UV)
40			1.1	6.0		1.0	4.4
50			1.1	7.1		1.5	4.9
60			0.9	6.5		2.0	5.4
70			1.0	6.5	1.3	3.0	5.8
80	1.6	1.6	1.0	6.4	1.4	4.0	6.0
90	1.3	1.7	1.0	6.0	1.4	5.0	6.1
99	1.0	1.5	1.2	6.1	1.6	5.5	6.1
$V_a/\text{V}$	5.5	3.0	1.0	5.5	5.5	$T/^\circ\text{C}$	70

$I_s$  [7], which implies a voltage-dependent  $Q_p/Q_s$  ratio. But this is no reason to reject this explanation, because actually the measured  $Q_p/Q_s$  also show a tendency to increase with higher voltage.

As a summary we can state that  $I_s$  mainly consists of the two last processes above.

In figure 7 the transferred charge  $Q_p$  is plotted against the measurement temperature for the different experiments. We can see that LC C has a higher ionic density compared to LCs A and B. However, this is no surprise since the bulk resistivity of the unprocessed LC was already lower. The explanation for this lower resistivity, earlier reported in [1], [3] and [16], is that LC C has a higher  $\bar{\epsilon}$ , so it is a more polar mixture in which ions are more easily dissolved. Also it is shown that our heat treatment and the 25 h UV illumination both make the ionic density rise by a factor 2 and 10 respectively.

Further, we can, again, fit an Arrhenius relation (6) to the results of each experiment

$$Q_p = B \exp\left(-\frac{W'}{kT}\right). \tag{6}$$

All measured values for  $W'$  are approximately 0.2 eV and only LC A after heat treatment is an exception (0.28 eV). The obvious explanation is that  $W'$  is the activation energy for the dissociation of a neutral species that is present into its ionic components. At this moment, the temperature range of our experiments is too small to obtain the full picture of the effects of temperature. It seems that the UV illumination has almost no influence and the heat treatment has only a small influence on the activation energy  $W'$ , but both have a strong influence on the constant  $B$ , representing the number of dissociable neutral species.

### 3.4. Resistivity

The (AC) resistivity of the LC in the LCD is given by equation (7) ( $n_i$  is the ionic density,  $e_i$  the charge and  $\mu_i$  the mobility of ionic species  $i$ , and  $Q_i$  is the amount of charge per  $\text{m}^2$  electrode (cell) area linked to ion  $i$ )

$$\rho = \frac{1}{\sum_i n_i e_i \mu_i} = \frac{d}{\sum_i Q_i \mu_i}. \tag{7}$$

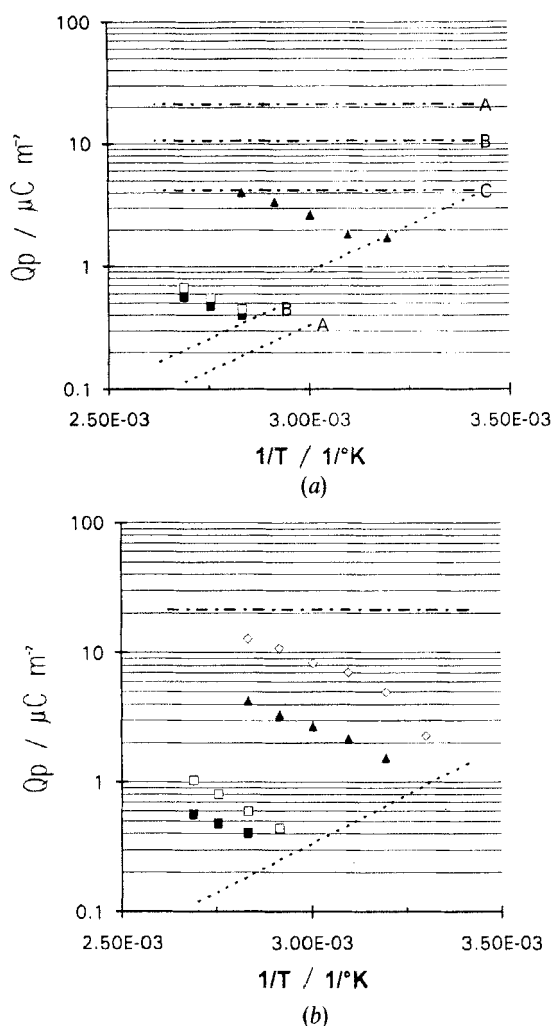


Figure 7. Measured transported charge  $Q_p$ : (a) LC A, B and C, (b) influence of UV and heat treatment on LC A. In (a), LC A is denoted by (■), LC B by (□), LC C by (▲), the SCL limit by (-----), and the noise limit by (-----). In (b), LC A is denoted by (■), LC A, 10 h at  $120^\circ\text{C}$ , by (□), LC A, 25 h UV illumination, by (▲), LC A, 50 h UV illumination, by (◇), the SCL limit by (-----) and the noise limit by (-----).

If we use only  $Q_p$  and  $\mu$  (extrapolated values if necessary), we obtain

LC	$\rho_{LC}$ , test cell, $60^\circ\text{C}/\Omega\text{cm}$	$\rho_{LC}$ , bulk, $60^\circ\text{C}/\Omega\text{cm}$
A	$3 \cdot 10^{12}$	$1 \cdot 10^{13}$
B	$3 \cdot 10^{12}$	$8 \cdot 10^{12}$
C	$3 \cdot 10^{11}$	$2 \cdot 10^{11}$

- (1) The calculated values are only rough estimations. Actually, they are still too high because we only used the ions presented in  $Q_p$ . If we take this remark into account, we can observe that the LC resistivity values from measurements on LC test cells are smaller than the values which have been obtained for the same LC from the bulk measurements. The decrease of the resistivity is largest in the

case of LC A and B ( $>4 \times$ ), the mixtures with the highest starting resistivity. This decrease could be attributed to the introduction of ionic species into the LC from the materials used in the cell construction [17, 18]. On the other hand, the resistivity of LC C remains practically unchanged. This might be due to the already low starting value of only about  $10^{11} \Omega \text{ cm}$ , which could have been less influenced by the introduction of a possibly constant amount of ionic impurities.

- (2) Both the heat and UV treatment lower the high resistivity in the LCDs because they increase the number of ions, not their mobility.
- (3) The resistivity in the LCDs in general decreases with temperature as in equation (8), with  $W''$  around 0.5–0.6 eV. In the temperature range 20–100°C this roughly means a decrease with a factor of 10 each time the temperature rises 40°C (see also [1, 3, 19]). This factor is higher than for the LC bulk resistivities of the unprocessed mixtures (see table 1). Again, this might be the consequence of pollution with new kinds of ions, introduced during the display processing. Maybe our decrease of  $\rho$  with temperature is also faster because we only used the ions that are presented in  $Q_p$ .

$$\rho \simeq \frac{d}{AB \exp\left(-\frac{W+W''}{kT}\right)} \sim \exp\left(\frac{W''}{kT}\right). \quad (8)$$

#### 4. Conclusions

Transient leakage current measurements are useful to obtain information about the density and the mobility of the ions present in LCs in LCDs. However, the method is somehow restricted to a particular narrow interval for the charge. But this difficulty can be lessened by using a better measurement system, a thinner LC layer and high threshold mixtures. The mobility and the amount of transported charge both depend on the temperature, following an Arrhenius relation, with an activation energy of 0.3 eV and 0.2–0.28 eV respectively. Obviously the mobility of the ions is mainly determined by the viscosity of the LC. The resistivity of the LC is dependent on the product of the mobility and the charge present, and decreases roughly with a factor of 10 each time the temperature rises 40°C.

UV illumination or heat treatment of the LCDs has very little effect on mobility of the ions, but a large effect on the ionic density.

We wish to thank the Belgian National Fund for Scientific Research (NFWO) and the Institute for Scientific Research in Industry and Agriculture (IWONL) for their financial support in this research.

#### References

- [1] RIEGER, B., PLACH, H. J., and NAEMURA, S., 1991, *Proceedings of the 5th Liquid Crystal Seminar* (organized by Merck Japan Ltd) p. 81. see also PLACH, H. J., WEBER, G., and RIEGER, B., 1990, *SID Int. Disp. Conf.*, p. 136.
- [2] VETTER, P., MAXIMUS, B., and PAUWELS, H., 1990, *SID Int. Disp. Conf.*, p. 320.
- [3] GROENEVELD, C. M., 1990, *SID Int. Disp. Conf.*, p. 324.
- [4] VETTER, P., 1991, Ph.D. Thesis, University of Ghent, Belgium.
- [5] DIJON, J., EBEL, C., VAUCHIER, C., BAUME, F., CLERC, J.-F., ESTOR, M., LEROUX, T., MALTESE, P., and MULATIER, L., 1988, *SID 1988 Digest*, p. 246.

- [6] DE LEY, E., and PAUWELS, H., 1990, *SID Int. Disp. Conf.*, p. 264.
- [7] CHIEU, T. C., and YANG, K. H., 1989, *Jap. J. appl. Phys.*, **28**, 2240.
- [8] MAXIMUS, B., DE LEY, E., DE MEYERE, A., and PAUWELS, H., 1991, *Ferroelectrics*, **121**, 103.
- [9] ZOU, Z., CLARK, N. A., and HANDSCHY, M. A., 1991, *Ferroelectrics*, **121**, 147.
- [10] MAXIMUS, B., VETTER, P., and PAUWELS, H., 1991, *SID IDRC, SID 1991 Digest*, p. 53.
- [11] VAXIVIÈRE, J., LABROO, B., and MARTINOT-LAGARDE, P. H., 1989, *Molec. Crystals liq. Crystals*, **173**, 61.
- [12] SIEDERLE, H., and SCHADT, M., 1992, *SID 1992 Digest*, p. 25.
- [13] NOVOTNY, V., and HOPPER, M. A., 1979, *J. electrochem. Soc.*, **126**, 925.
- [14] GALLAGHER, T. J., *Simple Dielectric Liquids: Mobility, Conduction, and Breakdown* (Clarendon Press), Chap. 1.
- [15] DE JEU, W. H., 1980, *Physical Properties of Liquid Crystalline Materials* (Gordon & Breach), Chap. 7.
- [16] WEBER, G., FINKENZELLER, U., GEELHAAR, T., PLACH H. J., RIEGER, B., and POHL, L., 1989, *Liq. Crystals*, **5**, 1381.
- [17] RIEGER, B., BOEHM, E., and WEBER, G., 1989, *Proceedings of the 18th Freiburger Arbeitstagung Flüssigkristalle 1989*, paper 16.
- [18] PLACH, H. J., RIEGER, B., WEBER, G., OYAMA, T., and SCHEUBLE, B. S., 1989, *Proceedings of the 3rd LC Seminar* (organized by Merck Japan Ltd).
- [19] COLPAERT, C., 1992, M.Sc., University of Ghent, Belgium.