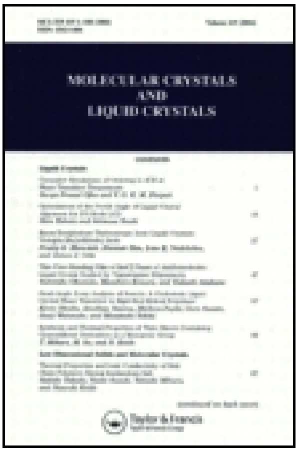

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Measurement of Rotational Viscosity and Pretilt Angle in Nematics from Transient Current

Masahiro Imai [a], Hiroyoshi Naito [a], Masahiro Okuda [a] & Akihiko Sugimura [b]

[a] Department of Physics and Electronics, University of Osaka Prefecture, 1-1 Gakuen-cho, Sakai, Osaka, 593, Japan

[b] Department of Information Systems Engineering, Osaka Sangyo University, 3-1-1 Nakagaito, Daito, Osaka, 574, Japan

To cite this article: Masahiro Imai , Hiroyoshi Naito , Masahiro Okuda & Akihiko Sugimura (1995): Measurement of Rotational Viscosity and Pretilt Angle in Nematics from Transient Current, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 262:1, 267-274

To link to this article: http://dx.doi.org/10.1080/10587259508033531

Mol. Cryst. Liq. Cryst. 1995, Vol. 262, pp. 267–274
Reprints available directly from the publisher
Photocopying permitted by license only

MEASUREMENT OF ROTATIONAL VISCOSITY AND PRETILT ANGLE IN NEMATICS FROM TRANSIENT CURRENT

MASAHIRO IMAI, HIROYOSHI NAITO and MASAHIRO OKUDA
Department of Physics and Electronics, University of Osaka Prefecture,
1-1 Gakuen-cho, Sakai, Osaka 593, Japan
AKIHIKO SUGIMURA
Department of Information Systems Engineering, Osaka Sangyo University,
3-1-1 Nakagaito, Daito, Osaka 574, Japan

Abstract Transient current technique is presented for measurement of rotational viscosity γ_1 and pretilt angle θ_0 in nematic liquid crystal display devices. Theoretical expressions for the determination of γ_1 and θ_0 from transient current are derived by taking account of the conduction of impurity ions and director rotation. Experimental results for γ_1 and θ_0 are compared with those with other conventional methods.

INTRODUCTION

We have developed an accurate and simple method for the measurement of rotational viscosity γ_1 and pretilt angle θ_0 of impurity-ion free nematic liquid crystals (NLCs) in device configurations using transient current technique.[1–3] Since NLC materials contain impurity ions, which are generated from more or less dissociated impurities as well as from the spontaneous dissociation of the NLC molecules themselves, the influence of ionic conduction on the analysis should be considered. By means of the method, not only γ_1-values but also θ_0-values can be measured in homogeneous[1,2] or twisted[3] configuration of NLC cells with common instruments. Further, the procedure for the determination of γ_1 is much simpler than optical[4,5] or capacitive[6] methods which require differentiation of transmittance or capacitance with respect to time, respectively, to measure with the same accuracy as the present method.

In this article, we demonstrate the applicability of the present method to NLCs containing impurity ions as well.

THEORY

We derive expressions for transient current in NLCs with homogeneous configuration excited by a dc step voltage V. The NLC layer is confined between the electrodes located at $z = 0$ and L. The tilt angle θ between the director and the z-axis is fixed to be θ_o at the electrodes, where θ_o is the pretilt angle.

We assume that the positive and the negative ions with the same density n in the NLC are uniformly distributed in thermal equilibrium state, and that the drift mobility μ of the positive ions is much larger than that of the negative ions. Here we focus ourselves on the time range $t \ll t_o$, where t_o [$= L/(\mu E)$] is the ion transit time, E is the applied electric field. In this time range, the net space charge density is zero and hence the Poisson equation is

$$\frac{\partial}{\partial z}\left[\varepsilon(\theta(z,t))E(z,t)\right] = 0 , \tag{1}$$

where ε is the dielectric permittivity of NLCs,

$$\varepsilon(\theta(z,t)) = \epsilon_o[\epsilon_\perp + \Delta\epsilon\cos^2\theta(z,t)] , \tag{2}$$

and ϵ_o is the dielectric permittivity of vacuum, $\epsilon_\perp$ is the dielectric constant normal to the director, and $\Delta\epsilon$ is the dielectric anisotropy. The conduction current due to the drift of the monovalent positive ions is written as $Sqn\mu E$ for $t \ll t_o$, where S is the area of the electrodes, and q is the electronic charge.

In the absence of flow, the director motion is expressed as[7]

$$\begin{aligned}\gamma_1\frac{\partial\theta}{\partial t} &= (K_{11}\sin^2\theta + K_{33}\cos^2\theta)\frac{\partial^2\theta}{\partial z^2}\\ &+\left[(K_{11}-K_{33})\left(\frac{\partial\theta}{\partial z}\right)^2 - \epsilon_o\Delta\epsilon E^2\right]\sin\theta\cos\theta ,\end{aligned} \tag{3}$$

where K_{11} and K_{33} are the splay and bend elastic constants, respectively. From the numerical analysis of Eqs. (1) - (3) under the strong anchoring conditions, the distributions of the director and the electric field along the z-axis are uniform during the director rotation for $V \geq 4\pi\sqrt{K_{11}/(\epsilon_o\Delta\epsilon)}$, except for those in the vicinity of the electrodes.[2] It is therefore reasonable to assume that the electric field in the bulk region E_b is approximately spatially uniform and time independent, and is given by[2]

$$E_b = \frac{V}{\left(1+\frac{\beta}{V}\right)L} , \tag{4}$$

where β is a positive constant. If the influence of the elastic deformation on the transient current can be neglected, β is equal to zero.

The total current $I(t)$ in NLCs is written as

$$I(t) = SE_\mathrm{b}\left[\frac{\mathrm{d}\varepsilon(\theta_\mathrm{b}(t))}{\mathrm{d}t} + qn\mu\right] , \tag{5}$$

where θ_b is the tilt angle in the bulk region. We find from Eqs. (2) - (5) that the current has a peak at $\theta_\mathrm{b} = 45°$. The peak current I_p which is the current at the peak is

$$I_\mathrm{p} = \frac{S(\epsilon_\mathrm{o}\Delta\epsilon)^2V^3}{2\gamma_1 L^3\left(1+\frac{\beta}{V}\right)^3} + \frac{Sqn\mu V}{L\left(1+\frac{\beta}{V}\right)} . \tag{6}$$

The peak time t_p at which the current has the peak is obtained as

$$t_\mathrm{p} = \frac{\gamma_1 L^2\left(1+\frac{\beta}{V}\right)^2 \log(\tan\theta_\mathrm{o})}{\epsilon_\mathrm{o}\Delta\epsilon V^2} , \tag{7}$$

where θ_o is the initial tilt angle, and $\theta_\mathrm{o} > 45°$ is necessary to observe the current peak. It is noted that θ_o does not contribute to I_p but to t_p.

EXPERIMENT

The NLC materials used in the transient current experiment were 4-cyano-4′-pentyl biphenyl (5CB), ZLI2293 from Merck, and fluorinate mixture A, B and C obtained from Matsushita Electric Industrial Co., Ltd. The NLC was introduced between two pieces of glass with a transparent $\mathrm{In_2O_3}$ electrode, whose area was 2 cm^2. We prepared three 5CB cells (5.3, 12 and 44 μm), a ZLI2293 (5.8 μm) cell, and fluorinate mixture A (4.8 μm), B (5.7 μm) and C (5.1 μm) cells, where the numerals in parentheses are the thickness of the cells. Polyimide alignment layers with 100 nm in thickness were coated on the electrodes except for the 12 μm 5CB cell. Substrate surfaces were unidirectionally rubbed in an antiparallel manner to produce homogeneous configuration.

A dc voltage pulse was applied to the cells at constant temperatures, where the NLCs were in the nematic phase. Transient currents were observed through a series load resistor by means of a wideband preamplifier and a digital storage oscilloscope. The measured data were transferred to a microcomputer for the analysis and the storage.

Representative current transients are shown in Figures 1(a) and 1(b) for the 12 μm 5CB cell at 303 K and the fluorinate mixture A cell at 293 K, respectively. A prominent current peak induced by director rotation is observed in each transient. Current baselines due to ionic conduction are not negligible in 5CB, but negligible in fluorinate mixtures and ZLI2293.

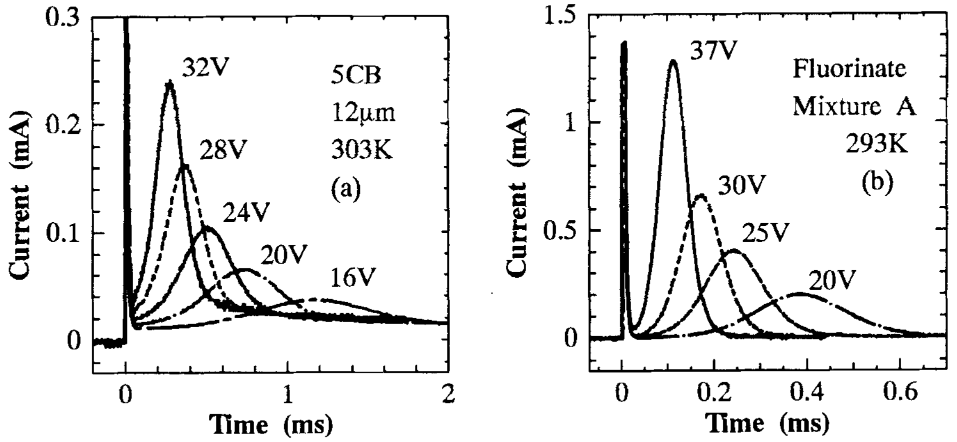

FIGURE 1 Transient current shapes of the 12 μm-thickness 5CB cell at 303 K (a) and of the fluorinate mixture A cell at 293 K (b).

RESULTS AND DISCUSSION

Influence of Ionic Conduction on Current Transients

We describe the results for 5CB, in which the influence of ionic conduction on the current cannot be neglected. It is assumed that the elastic deformation does not contribute to the current ($\beta = 0$) at high applied voltages. The applied voltages used here satisfy $V \gg \mu\gamma_1 \log(\tan\theta_o)/(\epsilon_o\Delta\epsilon)$, which is derived from $t_p \ll t_o$. At extremely high applied voltages, the initial charging current affects the current peak because the peak time becomes very short above certain applied voltage. Substituting $\beta = 0$ into Eqs. (6) and (7), we have

$$\frac{I_p}{E^3} = \frac{S(\epsilon_o\Delta\epsilon)^2}{2\gamma_1} + Sqn\mu\frac{1}{E^2}, \tag{8}$$

$$t_p = \frac{\gamma_1 L^2 \log(\tan\theta_o)}{\epsilon_o\Delta\epsilon V^2}. \tag{9}$$

We show plots of I_p/E^3 vs $1/E^2$ and t_p vs $1/E^2$ for the three 5CB cells at 303 K in Figures 2(a) and 2(b), respectively. Using $\Delta\epsilon$-value in the literature,[8] we obtain γ_1-values from the extrapolation of I_p/E^3 to $1/E^2 = 0$. We can also determine $qn\mu$- and θ_o-values from the slope of I_p/E^3 vs $1/E^2$ and of t_p vs $1/E^2$, respectively. These results at 303 K are summarized in Table I. The $qn\mu$-values are in the range 10^{-9}-10^{-10} S·cm^{-1}, consistent with those in the literature.[10] As listed in Table I, the γ_1-values for the different 5CB cells are the same, and the θ_o-values are the same for the cells with the same surface treatment.

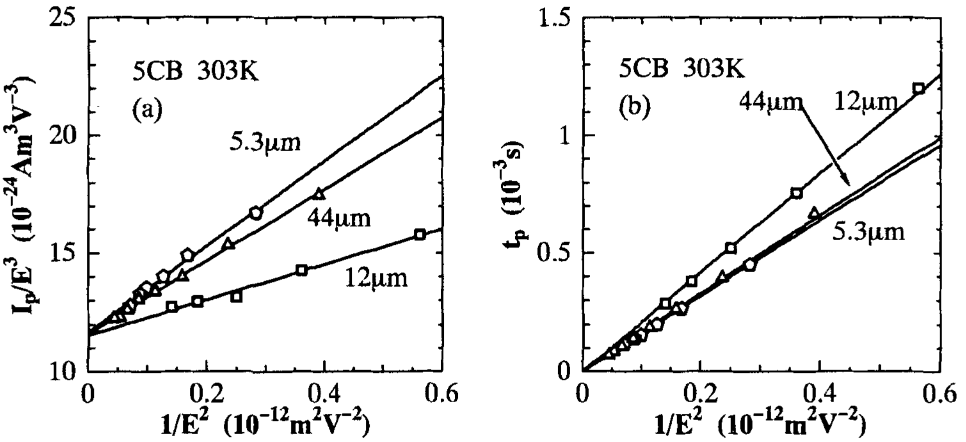

FIGURE 2 Plots of I_p/E^3 vs $1/E^2$ (a) and t_p vs $1/E^2$ (b) for the 5CB cells at 303 K.

TABLE I The rotational viscosity γ_1, the product of the density and drift mobility of the ions $qn\mu$, and the pretilt angle θ_o for the 5CB cells measured at 303 K.

L (μm)	Substrate surfaces	γ_1 (Pa·s)	$qn\mu$ (S·cm^{-1})	θ_o (°)
5.3	Polyimide	0.063	9.1×10^{-10}	83.5
12	In_2O_3	0.064	3.7×10^{-10}	86.5
44	Polyimide	0.063	7.6×10^{-10}	83.9

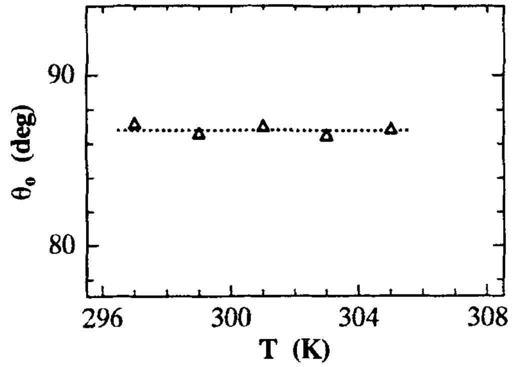

FIGURE 3 Temperature dependence of θ_o for the 5CB cell without polyimide alignment layers.

Temperature dependence of θ_o, γ_1 and $qn\mu$, which are measured in the 12 μm 5CB cell, is shown in Figures 3 and 4. We see that θ_o-values are independent of temperature because the temperature range is narrow and far from the transition temperature,[11] while the $qn\mu$-values exponentially vary with reciprocal temperature, whose activation energy is 0.77 eV. The γ_1-values are in agreement with those in the literature,[5,8,9] and especially, in excellent agreement with those by the electro-optic method.[5]

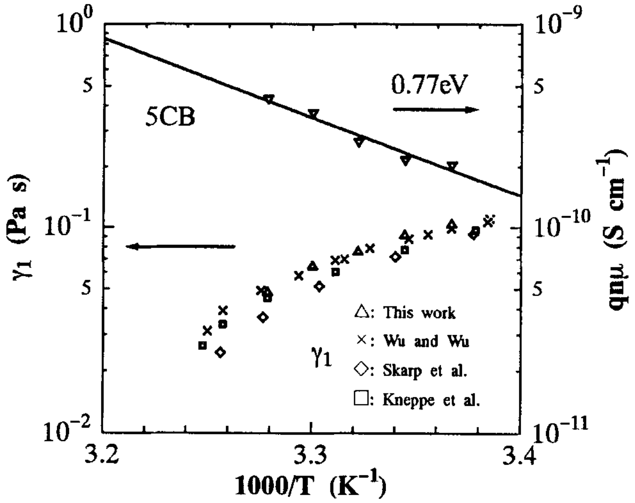

FIGURE 4 Temperature dependence of γ_1 and $qn\mu$ for the 5CB cell with 12 μm in thickness. △, ×, □ and ◇ represent the data points of γ_1 measured in this work, by Wu and Wu (Ref. 5), by Skarp *et al.* (Ref. 8), and by Kneppe *et al.* (Ref. 9), respectively. ▽ represents the data points of $qn\mu$ measured in this work.

Ionic Conduction Free Current Transients

We describe the results for the fluorinate mixtures and ZLI2293, in which the conduction current can be neglected in comparison with the displacement current. Thus, we reduce Eqs. (6) and (7) to

$$I_p^{-\frac{1}{3}}V = L\left(\frac{2\gamma_1}{S(\epsilon_o\Delta\epsilon)^2}\right)^{\frac{1}{3}}\left(1+\frac{\beta}{V}\right), \qquad (10)$$

$$\sqrt{t_p}V = L\sqrt{\frac{\gamma_1\log(\tan\theta_o)}{\epsilon_o\Delta\epsilon}}\left(1+\frac{\beta}{V}\right), \qquad (11)$$

respectively. If the contribution of the conduction current to the peak current is not negligible, the sign of β is negative. We can therefore experimentally check whether or not the conduction current is negligible from the sign of β.

Plots of $V/I_p^{1/3}$ vs $1/V$ and $\sqrt{t_p}V$ vs $1/V$ are shown in Figures 5(a) and 5(b), respectively, using the I_p- and t_p-values in the fluorinate mixture A, B and C at 293 K. We find that experimental data points lie on the straight lines, which are almost parallel to the horizontal axis, indicating that the elastic deformation does not greatly contribute to the current peak at high applied voltages. Using $\Delta\epsilon$-value, the γ_1-values can be determined from the extrapolation of $V/I_p^{1/3}$ to $1/V = 0$. The θ_0-values can also be determined from the extrapolation of $\sqrt{t_p}V$ to $1/V = 0$. The β-values do not affect the determination of γ_1 and θ_0. These results are shown in Table II. θ_0-values by this method are in good agreement with those by the crystal rotation method.[12]

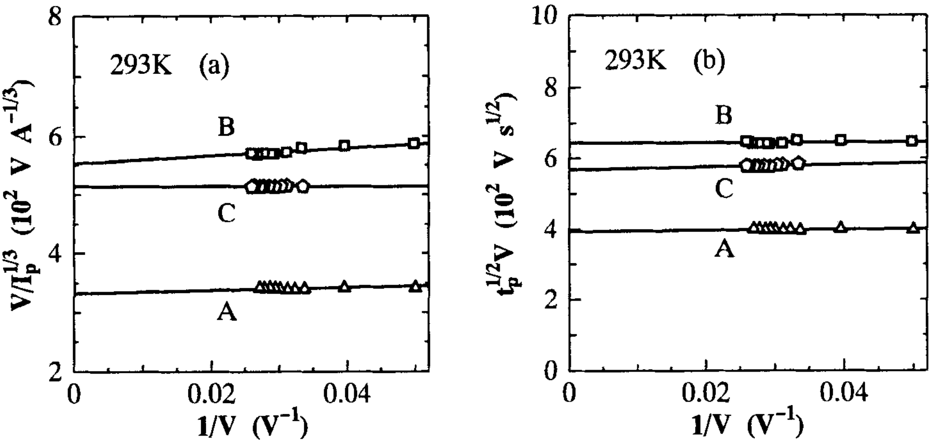

FIGURE 5 Plots of $V/I_p^{1/3}$ vs $1/V$ (a) and $\sqrt{t_p}V$ vs $1/V$ (b) at 293 K. A, B and C represent the fluorinate mixture A, B and C, respectively.

TABLE II Physical properties of fluorinate mixture A, B and C at 293 K. The dielectric anisotropy $\Delta\epsilon$ measured at 1 kHz by the dielectric method (Ref. 13). The pretilt angle θ_0 measured by the crystal rotation (CR) method and the present transient current (TC) method. The rotational viscosity γ_1 measured with the TC method.

Sample	L (μm)	$\Delta\epsilon$	θ_0 (°) [CR]	θ_0 (°) [TC]	γ_1 (Pa·s) [TC]
A	4.8	7.6	87.1	87.1	0.15
B	5.7	5.2	85.4	87.2	0.19
C	5.1	5.5	87.1	85.4	0.24

We also measure γ_1- and θ_0-values of the ZLI2293 cell by the same procedure as those for the fluorinate mixtures.[1,2] The γ_1-values measured in this work are in excellent agreement with the Merck data.[14] The temperature dependence of θ_0-values is also in excellent agreement with that in the literature.[11]

CONCLUSIONS

We have derived the expressions relating the peak current and peak time in the transient current to the physical quantities (γ_1, $\Delta\epsilon$, θ_o and $qn\mu$). Based upon these equations, we have developed the procedure to determine the physical quantities such as γ_1 and θ_o of the NLC cells and have examined the procedure for NLCs with or without impurity ions.

We have measured the transient current of 5CB, ZLI2293 and fluorinate mixtures (A, B and C) at nematic temperatures. The conduction current is not negligible in 5CB, but negligible in ZLI2293 and the fluorinate mixtures. We have determined the γ_1-, θ_o- and $qn\mu$-values of the 5CB cells and the γ_1- and θ_o-values of the ZLI2293 cell and the fluorinate mixture cells with this method. The γ_1-values of 5CB and ZLI2293 are in agreement with those in the literature. The θ_o-values of the fluorinate mixtures are in agreement with those using the crystal rotation method.

ACKNOWLEDGMENTS

The authors would like to thank Mr. K. Hattori, Mr. H. Wakemoto and Mr. H. Kubota, Matsushita Electric Industrial Co., Ltd., for the preparation of the samples and for the crystal rotation measurement. The authors would like to thank E. Merck for supplying ZLI2293. One of the authors (M. I.) would like to thank Association for Promotion of Electrical, Electronic and Information Engineering for finantial support.

REFERENCES

1. M. Imai, H. Naito, M. Okuda and A. Sugimura, Jpn. J. Appl. Phys., **33**, L119 (1994).
2. M. Imai, H. Naito, M. Okuda and A. Sugimura, Jpn. J. Appl. Phys., in press.
3. M. Imai, H. Naito, M. Okuda and A. Sugimura, unpublished.
4. F. Brochard, P. Pieranski and E. Guyon, Phys. Rev. Lett., **28**, 1681 (1972).
5. S. T. Wu and C. S. Wu, Phys. Rev. A, **42**, 2219 (1990).
6. P. R. Gerber, Appl. Phys. A, **26**, 139 (1981).
7. P. G. De Gennes, *The Physics of Liquid Crystals* (Oxford University Press, London, 1974). p. 158.
8. K. Skarp, S. T. Lagerwall and B. Stebler, Mol. Cryst. & Liq. Cryst., **60**, 215 (1980).
9. H. Kneppe, F. Schneider and N. K. Sharma, J. Chem. Phys., **77**, 3203 (1982).
10. A. Ashford, J. Constant, J. Kirton and E. P. Raynes, Electron. Lett., **9**, 118 (1973).
11. H. A. van Sprang and R. G. Aartsen, J. Appl. Phys., **56**, 251 (1984).
12. T. J. Sheffer and J. Nehring, J. Appl. Phys., **48**, 1783 (1977).
13. T. Uchida and Y. Takahashi, Mol. Cryst. & Liq. Cryst., **72**, 133 (1981).
14. Merck Liquid Crystals Catalogue (E. Merck).