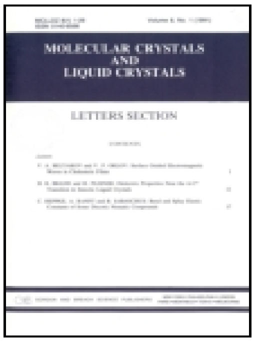

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Measurement Method for Flexoelectric Coefficients of Nematic Liquid Crystals by Means of Symmetrically Oblique Incidence Transmission Ellipsometry

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Improved measurement method for the flexoelectric coefficients of nematic liquid crystal based on the renormalized transmission ellipsometry is demonstrated. For eliminating the inaccuracy in the measurement of retardation caused by multiple-beam interference in anisotropic multilayer-structured thin films, symmetrically oblique incidence transmission Ellipsometry (SOITE) has proposed and applied to the determination of the device parameters such as the cell gap, surface anchoring energy, reduced dielectric anisotropy and reduced elastic constant. We applied the SOITE technique to determine the flexoelectric coefficients ($e_{11} + e_{33}$) for the splay and bend distortion.

Keywords Flexoelectric coefficient; nematic liquid crystal; ellipsometry; hybrid alignment

1. Introduction

One of a specific feature of a homogeneously aligned liquid crystal layer is spontaneous polarization *P* which arises in response to elastic deformation such as splay and bend, which is so-called "flexoelectric effect," which have been described by Robert Meyer in 1969 [1]. In nematic liquid crystals, the transverse and longitudinal deformations give rise to two independent flexoelectric coefficients e_{11} and e_{33}. Recently, the study of the flexoelectric effect has attracted the attention of many researchers because of its applicability to fast response liquid crystal displays (LCDs). One hand, D. J. Gardiner *et al.* [2] demonstrated that the flexoelectro-optic effect provides a fast-switching response. An in-plane electric field is applied to a short-pitch chiral nematic liquid crystal aligned in the uniform standing

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helix texture. F. Castles *et al.* [3] showed theoretically that flexoelectricity stabilizes blue phases in chiral liquid crystals. Induced internal polarization reduces the elastic energy cost of splay and bend deformations surrounding singular lines in the director field. On the other hand, flexoelectric effect is considered to be the cause of the image sticking problem [4–6]. Up to today, several kinds of measurement technique have been proposed. As is summarized in the literature [7], the sign and/or the absolute value of the measured flexoelectric coefficients with regards to a common nematic liquid crystal (NLC) differs for every published paper. Similarly, many approaches with regard to the determination of polar anchoring energy coefficient were intensively studied [8]. 9 years ago, our group has demonstrated a simplified but accurate measurement technique, we named "symmetry oblique incident transmission ellipsometry" (SOITE). Hung *et al.* proposed a method of determining polar anchoring energy coefficient based on the SOITE method, [9,10] which can determine simultaneously six device parameters of LCDs by perfectly eliminating the effect of multiple-beam reflection (MBR) and multiple-beam interference (MBI) [10]. In this study, we tried to apply the SOITE to determine the flexoelectric coefficient by using hybrid alignment liquid crystal cells.

2. Phase Difference Derived from the Continuum Theory

The detailed numerical derivation with regard to the director distortion inside a simple hybrid aligned nematic (HAN) cell was described in our previous paper [11]. The bulk free energy density can be expressed by the prototypical equation as follows;

$$W = \frac{1}{2} f_{\text{elas}}(\theta) \left(\frac{\partial \theta}{\partial z}\right)^2 - \frac{1}{2} f_{\text{diel}}(\theta) \left(\frac{\partial \varphi}{\partial z}\right)^2 + f_{\text{flex}}(\theta) \cos\theta \left(\frac{\partial \theta}{\partial z}\right)\left(\frac{\partial \varphi}{\partial z}\right), \quad (1)$$

where $\theta(z)$ is the polar angle with respect to the x-y plane (viz. substrate surface), Frank's elastic free energy density $f_{\text{elas}}(\theta) = K_{11}\cos^2\theta + K_{33}\sin^2\theta$, dielectric free energy density $f_{\text{diel}}(\theta) = \varepsilon_0(\varepsilon_{\text{p}}\sin^2\theta + \varepsilon_{\text{n}}\cos^2\theta)$, and flexoelectric free energy density $f_{\text{flex}}(\theta) = (\text{e}_{11} + \text{e}_{33})\sin\theta\cos\theta$, respectively. ε_{p} and ε_{n} represent dielectric constant parallel and perpendicular to the director. φ is the electric scalar potential written by

$$\text{V} = \int_0^{\text{d}} \left(\frac{\partial \varphi}{\partial \text{z}}\right) \text{dz}, \quad (2)$$

where V is the applied DC voltage to the HAN cell. Planar anchoring energy at the bottom ($z = 0$) and top ($z = d$) substrate surface is given in the conventional Rapini-Papoular form;

$$\begin{aligned} f_{s0} &= \tfrac{1}{2} A_{\theta 0} \sin^2(\theta_{[0]} - \theta_0), \\ f_{sd} &= \tfrac{1}{2} A_{\theta d} \sin^2(\theta_{[d]} - \theta_d), \end{aligned} \quad (3)$$

where θ_0 and θ_d express the angle of the easy axis on each substrate surface, and $\theta_{[0]}$ and $\theta_{[d]}$ express the actual angle of the director with respect to the substrate surface, respectively. $A_{\theta 0}$ represents the planar anchoring energy coefficient at the bottom substrate, and $A_{\theta d}$ represents the vertical anchoring energy coefficient at the top substrate, respectively. The free energy density is expressed by the summation of eqs.(1) and (3), and the free energy per unit area of the HAN cell is obtained by the integration to the direction of cell thickness (z direction). The Euler-Lagrange equations of the bulk, surface and electric scalar potential are derived to calculate field-induced deformations of the director distribution throughout

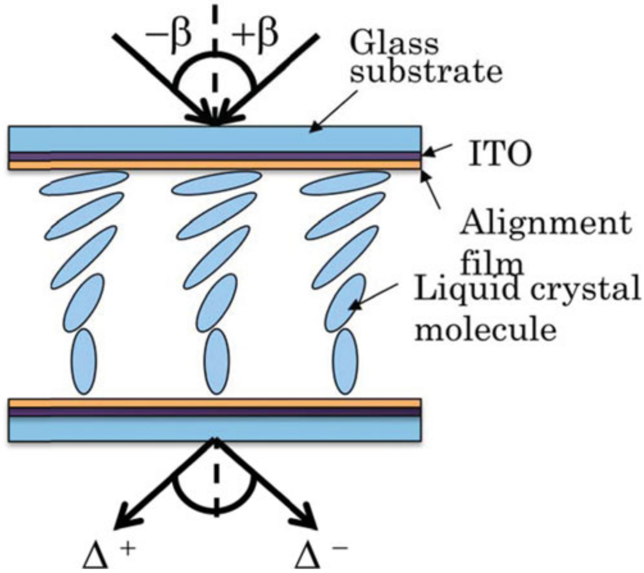

Figure 1. Arrangement of the sample HAN cell and the incidence angle β.

the cell $\theta(z)$. The ellipsometric parameter $\Delta(\lambda)$, which represents the phase difference at the wavelength λ, is measured not by normal incidence but by oblique incidence. Figure 1 shows the arrangement of the sample HAN cell and the incidence angle β. The phase difference for $+\beta$ and $-\beta$ incidences (say Δ^+ and Δ^-) is experimentally measured by the spectroscopic ellipsometer. As is described in our previous paper, [9] Δ^+ and Δ^- hold $\Delta^- - \Delta^+ = R^- - R^+$, where R^- and R^+ represent the retardation of the HAN cell when the incidence angle is $-\beta$ or $+\beta$, respectively. $\Delta^- - \Delta^+$ can be expressed by θ as follows;

$$\Delta^- - \Delta^+ = \frac{4\pi}{\lambda} \sin\beta \int_0^d \frac{\nu \cos\theta \sin\theta}{1 + \nu \sin^2\theta} dz, \tag{4}$$

where $\nu = ({n_e}^2 - {n_e}^2)/{n_e}^2$. At last, $e_{11} + e_{33}$ can be determined by the numerical fitting procedure.

Table 1. Physical parameters of LC materials used in our experiments (25°C)

	K_{11} (pN)	K_{33} (pN)	ε_p	ε_n	n_e	n_o	$e_{11} + e_{33}$ (pC/m)
ZLI-2293	12.5	16.9	14.1	4.1	1.63	1.5	0
ZLI-4792	13.2	18.3	8.3	3.1	1.57	1.48	0
MLC-2038	13.8	18.1	4.0	9.0	1.58	1.48	20
MLC-6608	16.7	18.1	3.6	7.7	1.55	1.47	15

@1 kHz @589.3 nm.

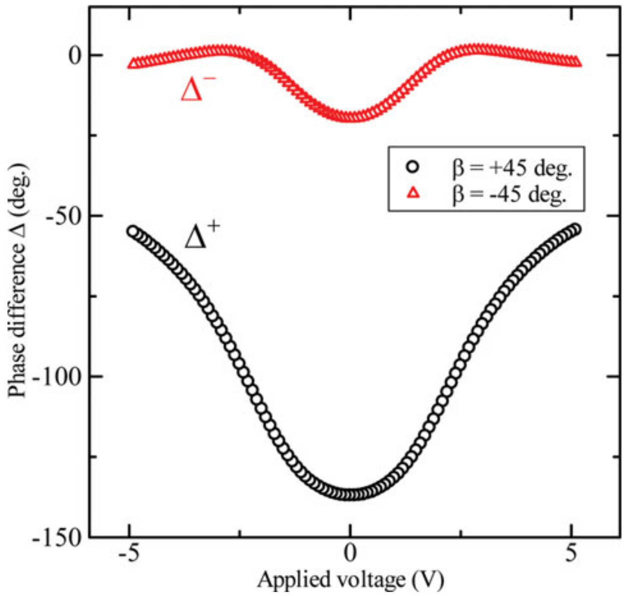

Figure 2. Experimentally measured Δ^+ and Δ^-, where the sample LC is MLC-6608.

3. Experimental

Conventional sandwich type cell with Indium Tin Oxide electrodes was prepared, whose lower glass substrate surface was covered by a prerubbed polyimide for planar alignment,

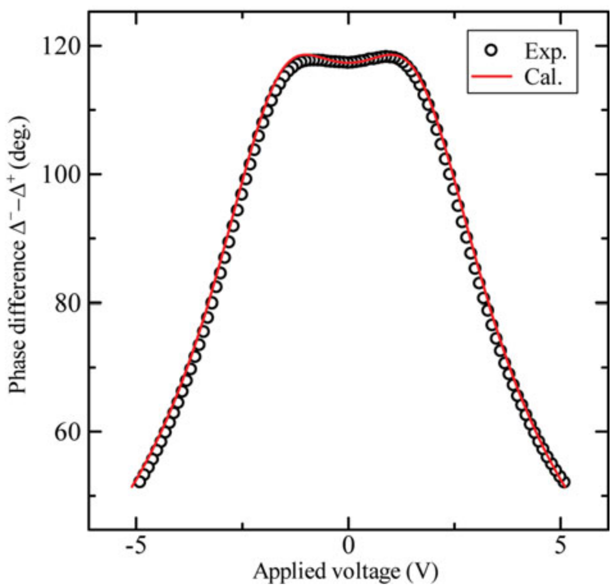

Figure 3. Applied voltage dependence of $\Delta^- - \Delta^+$, open circle represents the experimental result, and solid red line represents the numerical fitting.

and upper glass substrate was covered by another type of polyimide for vertical alignment. The nominal cell gap is 5 μm. Applied vertical electric voltage is ranging −10 V to 10 V. The wavelength of the ellipsometer was set at $\lambda = 589.3$ nm, and the incidence angle is set −/+45 degrees. The physical parameters of LC materials used in our experiments (supplied by Merck Ltd. Japan) are listed in Table 1. The anchoring energy coefficients are supposed to be $A_{\theta 0} = 3.7 \times 10^{-3}$ J/m^2 and $A_{\theta d} = 1.0 \times 10^{-3}$ J/m^2.

4. Results and Discussion

Figure 2 shows one of a typical example of the experimentally measured Δ^+ and Δ^- of HAN LCD sample cell under the applied DC voltage, where the sample LC is MLC-6608. The incident angle $\beta = 45^{\circ}$ and $\lambda = 589.3$ nm. From these experimental data, the applied voltage dependence of $\Delta^- - \Delta^+$ is depicted in Figure 3. The solid line indicates the results of the numerical fitting calculation. It is found that the outline of the $\Delta^- - \Delta^+$ looks like a side view of mountain, and the right side bump is tiny bit higher than the left side bump as is indicated with a horizontal line. The difference of height corresponds to the value of $e_{11} + e_{33}$. By minimizing the square errors between the calculated and experimentally measured values of $\Delta^- - \Delta^+$, subject cell parameters d and $e_{11} + e_{33}$ were obtained simultaneously. The obtained $e_{11} + e_{33}$ of four LC mixtures are also listed in Table 1. The measurement resolution seems to be approximately 5pC/m at most. As is reported by the past literatures, the resolution is also affected by the sample condition such as the purity of LC and surface alignment films [12].

5. Conclusion

In this paper, it is proposed that the flexoelectric coefficient $e_{11}+e_{33}$ can be estimated by the Symmetric-Oblique Incident Transmission Ellipsometry. Experimentally measured phase difference was found to be in good agreement with the numerical result without disturbance by the multiple beam interference. The resolution is 5pC/m at most because of the sample condition such as the purity of LC and the surface alignment films. Estimation of the flexoelectric coefficient $e_{11}-e_{33}$ is now attempting using Ellipsometry.

Acknowledgments

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