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In this study, we report on evaluation of liquid crystal (LC) cells using simultaneous surface plasmon resonance (SPR) and optical waveguide spectroscopy (OWS) technique in attenuated total reflection configuration. This technique allows for in-situ monitoring of alignment property of LC molecules adjacent to the surface and the bulk in the LC cell simultaneously. An increase of the hysteresis both for near the surface and whole cell was observed in SPR/OWS kinetic properties as the number of voltage cycling increased. The LC alignment properties after applying a DC voltage were also measured to study the effect of impurity residual ions in LC cells.

Keywords 5CB; image-sticking; OWS; SiO_2 alignment layer; SPR

1. Introduction

In recent years, there has been increasing demands for various liquid crystal (LC) devices such as LC displays in practical use. One of the challenges for further development is to overcome the problems in their reliability. The phenomenon called "Image-sticking," which causes an afterimage when displayed for a long time, is one of the typical problems. It is well known that the problem is caused by impurity ions in LC materials [1–3]. However, the mechanism remains incompletely understood because the evaluation of LC molecules adjacent to the electrode is difficult due to complex interaction between the components such as electrodes and alignment layers. Therefore, effective evaluation methods of interfacial phenomenon are desired. It is important to clarify the detail of LC alignment state, especially the LC/alignment layer interface in order to understand the mechanism.

Surface plasmon resonance spectroscopy (SPR) using attenuated total reflection (ATR) method [5–7], the second harmonic generation method [8] and the total

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reflection ellipsometry method [9] have been reported for the study of alignment properties of LC molecules on the alignment layers, Recently, we have also reported simultaneous SPR and optical waveguide spectroscopy (OWS) technique for the evaluation of LC molecules on polyimide Langmuir-Blodgett (LB) and layer-by-layer alignment layers [10–12].

In this study, we report on the evaluation of tilt angles of LC molecules near the surface of SiO_2 alignment layers and in the whole cell when constant voltages are applied. Surface plasmon resonance spectroscopy and waveguide modes in attenuated total reflection configuration are used to monitor the orientation property of LC molecules on the surface and the bulk. The kinetic measurement during voltage cycling allows in-situ observation of tilt angles of LC molecules from near the alignment layers to the inside the LC cell. LC alignment properties after applying a DC voltage were also measured to study the effect of impurity residual ions in LC cells.

2. Experimental Section

2.1. *Sample Preparation*

The sample structure of LC cell consisted of Au (50 nm)/SiO_2 (30 nm)/LC/SiO_2 (30 nm)/Au (100 nm) as schematically shown in Figure 1. Gold (Au) thin films, thickness of ca. 50 and 100 nm, were DC-sputtered on high refractive index glass (S-LAH59: n = 1.8124 Ohara Inc.) and standard glass substrates (BK-7: n = 1.52), respectively. SiO_2 alignment layers, thickness of 30 nm, were deposited on both Au/glass substrates by oblique evaporation using an ion assist deposition (IAD) instrument. 4-Cyano-4′n-pentylbiphenyl (5CB, Merk JAPAN) was used as the LC molecule, and the cell gap was about 3 μm. The LC cell was attached to the flat side of the half cylindrical prism (S-LAH60: n = 1.8294, Ohara Inc.) with index matching oil as shown in Figure 1. The sample was mounted on a θ-2θ stage for the angular measurements.

2.2. *SPR/OWS Measurement*

A p-polarized He-Ne laser ($\lambda = 632.8$ nm) was used for the measurements. The laser light was irradiated from the half cylindrical prism (S-LAH60: n = 1.8294, OHARA Inc.) side. The LC cell was attached to the flat side of the prism with index matching oil. The sample was mounted on a θ-2θ goniometer. The temperature of the LC cell was controlled by Peltier elements. Details of the system are described elsewhere [10].

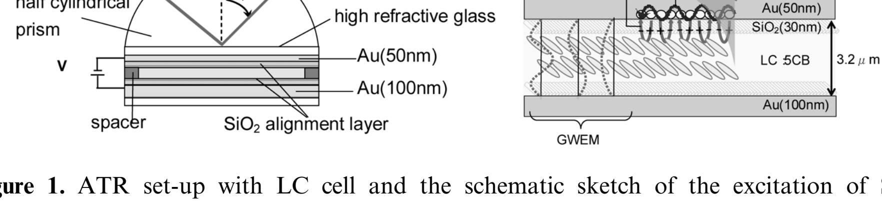

Figure 1. ATR set-up with LC cell and the schematic sketch of the excitation of SPR and OWS.

3. Results and Discussion

3.1. *Angular SPR/OWS Properties at Constant Applied Voltages*

First, angular properties were studied at constant applied voltages, 0, 2, 4, and 10 V at ambient temperature as shown in Figure 2(a). The SPR dips, which depend on the tilt angles of LC molecules adjacent to the surface of the alignment layer, were observed at around 68° at 0 and 2 V. The SPR dip above 4 V shifted to higher angles with an increase of the applied voltage. This shift indicates an increase of the tilt angle near the surface, i.e., horizontally aligned LC molecules gradually tilt toward vertical direction. On the other hand, OWS dips were changed at all the applied voltages, indicating that the average tilt angles of LC molecules in the whole cell tilt toward vertical direction. It should be noted that OWS dips largely changed at low applied voltages, while SPR dip changed at above 4 V. This result means that the simultaneous SPR/OWS technique provides the information of tilt angles of LC molecules both near the surface and the average value in the whole cell. To evaluate tilt angles of LC molecules, theoretical curve fittings to the experimental results were carried out by Fresnel calculation [13]. In the calculation, the LC layers, thickness of 3.2 ~ 3.5 μm, were divided into 5 parts as illustrated in Figure 3(a) because the tilt angles gradually change from near the interface to middle of the cell. The dielectric constant of the LC molecule was obtained from a reported value [14]. Figure 3 (b) is an example of the fitting result. As shown in this figure, both the calculated SPR and OWS dips were corresponded well with the experimental result. From the theoretical fittings, the tilt angles from the interface of alignment layer to middle of the LC cell were obtained for all the applied voltages. As shown in Figure 3(c), the tilt angle near the surface gradually change from 3° at 0 and 2 V to 26° at 10 V. On the other hand, the tilt angle at the middle of the cell change more sensitively, i.e., 5° at 0 V to 90° at 10 V.

In order to further study the change of the tilt angles with applied voltages, the kinetic properties were measured at fixed incident angles of 43° and 67.4°, which correspond to OWS and SPR dips as indicated by solid lines in Figure 2, during the voltage cycling from −3 to +3 V at 10 mHz for 3 cycles. As shown in

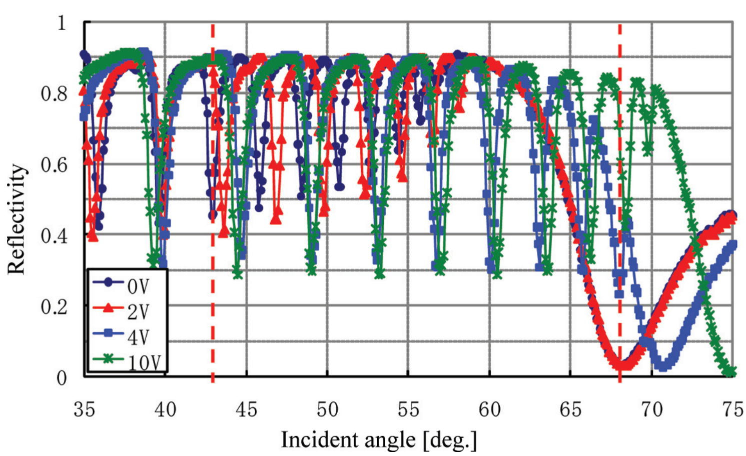

Figure 2. Angular SPR/OWS properties at different applied voltages as indicated.

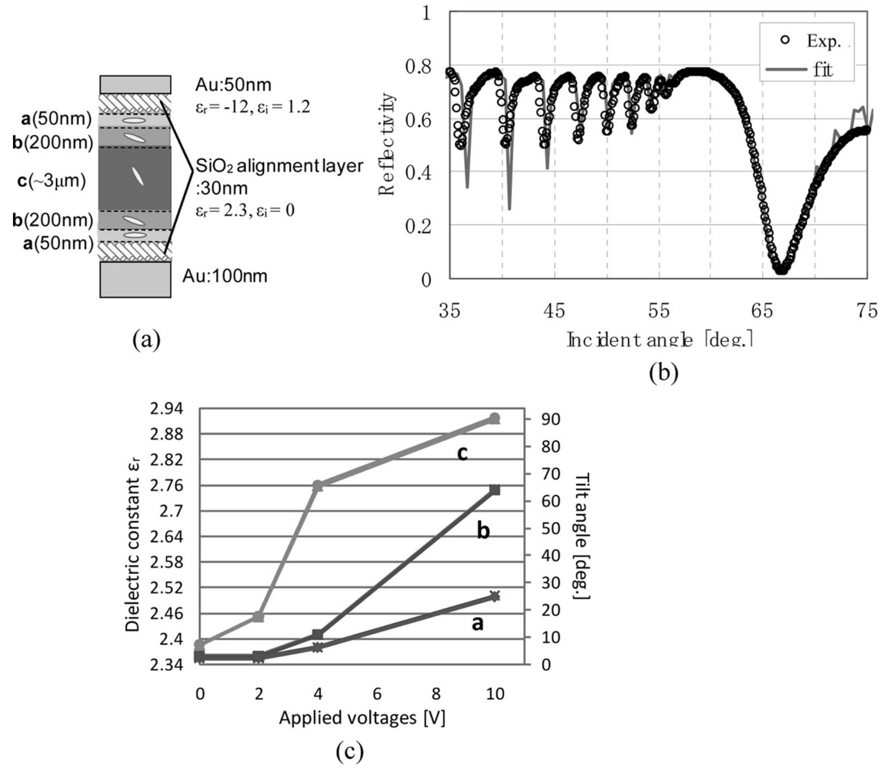

Figure 3. Structure of the LC cell divided into 5 layers (a), Experimental (dotted) and simulated (solid) SPR/OWS curves (b), and Dielectric constants/tilt angles of LC molecules at each area as a function of applied voltages.

Figure 4(a) and (b), the reflectivity of the OWS dip at 43° increased at around 1 V in 1st cycle, while SPR dip at 67.4° did not increased up to 2 V. This is because of the anchoring force of the SiO_2 alignment layers [15–17] One can find the fact that a hysteresis was observed both for OWS and SPR dips. At following cycles, the hysteresis

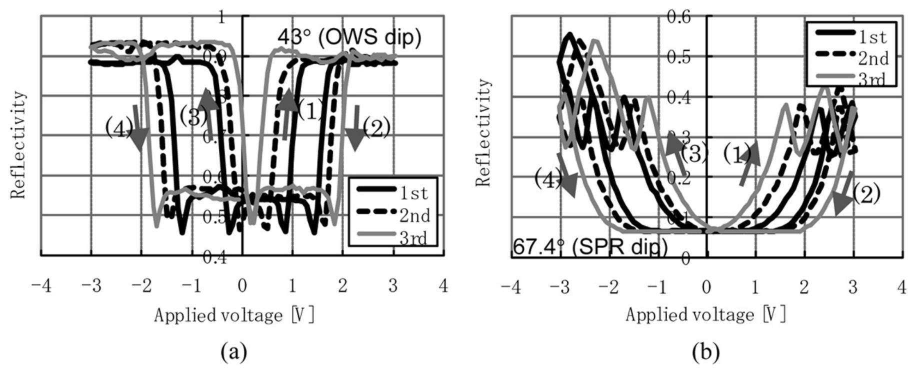

Figure 4. Kinetic OWS (at 43°) and SPR (at 67.4°) properties measured from −3 to + 3 V for 3 cycles at a scan rate of 10 mHz.

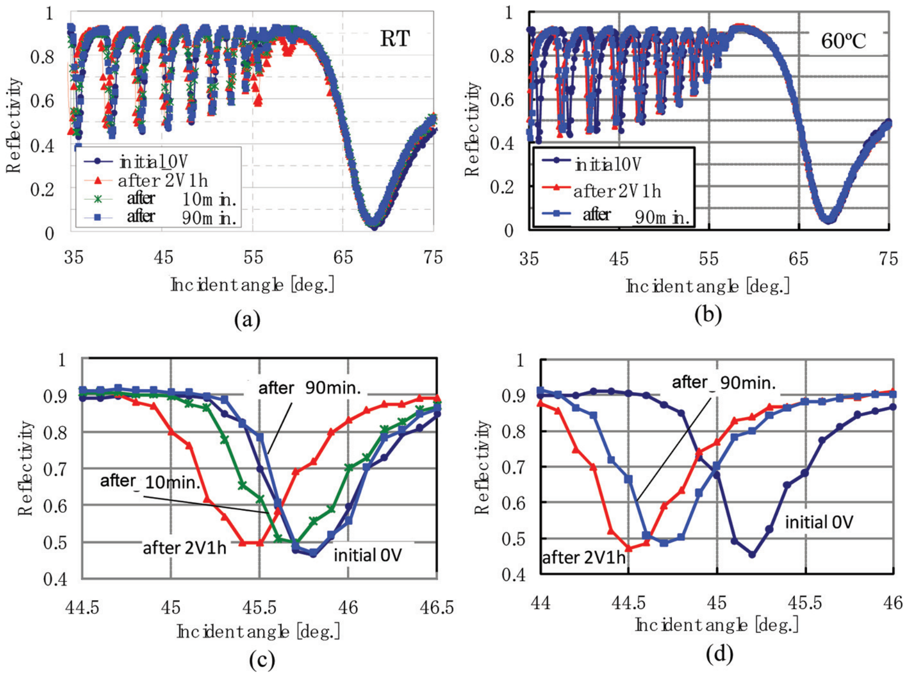

Figure 5. Angular SPR/OWS properties measured before and after applying the voltage at 2 V for one hour at ambient temperature (a) and 60°C (b). After applying the voltage, the angular properties were measured immediately at ambient temperature, and also measured after 10 min. and 90 min. after leaving at ambient temperature as indicated. Enlargements of OWS dips in (a) and (b).

becomes larger as the cycle number increase, which might be responsible for space-charge polarization due to impurity ions.

3.2. *LC Alignment Property After Applying the Voltage*

In order to study the effect of impurity ions in the LC cell which relates to "Image-sticking" problem in LC displays, angular SPR/OWS properties were measured after applying the voltage at 2 V for one hour at ambient temperature and 60°C. After applying the voltage, the angular properties were measured immediately at ambient temperature, and also measured after 10 min. and 90 min. after leaving at ambient temperature. Figure 5 shows angular properties measured before and after applying the voltage. In both cases, the SPR dips were almost constant. This indicates that the tilt angle near the surface is stably moved back to initial state after applying the voltage. On the other hand, the OWS dips at 60°C were obviously changed after applying the voltage. Figure 5(c) and (d) show enlargements of OWS dips in Figure 5(a) and (b), respectively. As shown in this figure, the OWS dip after applying 2 V at 60°C shifted much larger than that of ambient temperature. Furthermore, OWS dip after applying 2 V at 60°C did not shifter back to initial position even after leaving at ambient temperature for 90 min, while the OWS dips after applying 2 V at ambient temperature moved back to initial position. In general, the impurity ion problem occurs when the LC displays are driven at higher temperature. Hence, this result should indicate that the impurity ions affected the LC alignment which relates to "Image-sticking" problem.

4. Conclusions

In conclusion, we have studied the alignment properties of LC molecules on SiO_2 alignment layers, which showed different alignment properties between inside of the cell and near the interface at several constant voltages. These results were obtained by simultaneous surface plasmon resonance (SPR) and optical waveguide spectroscopy (OWS) technique. In-situ measurements to study the change of LC alignment during the voltage sweep were carried out by SPR/OWS technique. SPR/OWS kinetic properties showed a hysteresis which increased as the number of voltage cycling increased. Furthermore, LC alignment properties after applying the voltage, which might be related to the "Image-striking" effect, were observed. As demonstrated in this report, this technique should provide a useful information to understand the phenomena for LC displays at the interface.

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