Mechanism of image sticking after long-term AC field driving of IPS mode

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Abstract — An AC electric field to drive the IPS mode of a liquid-crystal display (LCD) causes a reduction in the contrast after a long period of display operation. This phenomenon is refered to as the AC image-sticking problem caused by long-term driving. Thus far, there is no useful method of quantitatively evaluating AC image sticking. LCD panel products that use the IPS mode have been evaluated for a decade. In this paper, a new evaluation parameter ($\Delta\theta$), which was recently proposed by Suzuki *et al.,* is introduced. It was calculated from the slight difference in the deviation angle of LC molecules from the rubbing direction. Results from several conditions of test samples are presented in this paper as a phenomena that reflect the interaction between the surface of the PI alignment and the LC molecules. The results and discussions describe reasons for azimuthal gliding after long display operation for weak AC voltage driving. It is explained by suitably adopting the Kelvin–Voigt model which is used to discuss the rheology of viscoelastic material. It is concluded that the surface rheology of PI alignment is one of the most important factors for the contrast reduction of the AC image-sticking problem.

Keywords — *IPS, image sticking, azimuthal anchoring, PI, surface rheology.*

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1 Objective and background

Among the varieties of LCD modes, the IPS mode has merits for wider-viewing-angle and color-shift parameters. LC molecules in the IPS mode are aligned by a rubbing method and are reoriented by means of an AC driving voltage so that the retardation of the incident polarized light from a backlight unit can be controlled. The twist direction of the reorientation is uniquely determined depending on the direction of rubbing and the electrodes. When we apply long-term driving to an IPS-mode display, the continuing twist motion is memorized as the irreversible director deviation of the LC molecules from surface PI alignment. This deviation causes a reduction in the quality of the contrast level of the IPS mode.

We examined the mechanism of the above memory effect in this paper. We measured the black brightness of simple test cells with an electrode with a bending-comb teeth-shaped structure, which was proposed by Suzuki *et al.*[1] to obtain the "gliding angle" $\Delta\theta$ for the characterization of the memory effect. We characterized $\Delta\theta$ based on the period of AC driving by long continuous measurement. We confirmed that $\Delta\theta$ is useful as the evaluation parameter of the AC image-sticking problem by exactly measuring $\Delta\theta$ for AC driving for about 1 month.

TABLE 1 — Process conditions.

Sample No.	PI Material	Post Bake (℃)	Pile Impression (mm)	Cell Gap (µm)	LC Material
1	SE7492	170	0.1	3	ZLI4792
2		200			
3		230			
4			0.2		
5			0.3		
6			0.4		
7		Skip	0.1		

2 Experiment

We prepared test cells of a simple structure that had bended-comb-teeth ITO electrodes as described in Fig. 1. The electrode area was 1×1 cm. The spacing between electrodes was 10 µm. The angle of the electrodes and LC alignment direction was 20°. We set one glass substrate having electrodes on another plain non-conductive substrate using a column spacer with a 3-µm height. Table 1 shows the preparation condition of sample cells. PI film (Nissan Chem. SE7492, 1000 Å thickness) on each substrate was coated by a spin coater and baked at three conditions of 170, 200, and 230°C for 30 minutes in a heat chamber. For sample No. 7 of Table 1, the post-bake process was eliminated. Rubbing was processed with four pile impressions – 0.1, 0.2, 0.3, and 0.4 mm. The pile impression was a distance from the rubbing zero point indicating the rubbing strength. A larger pile impression corresponds to stronger rubbing. A heat sealant of an epoxy type was dispensed around the edge

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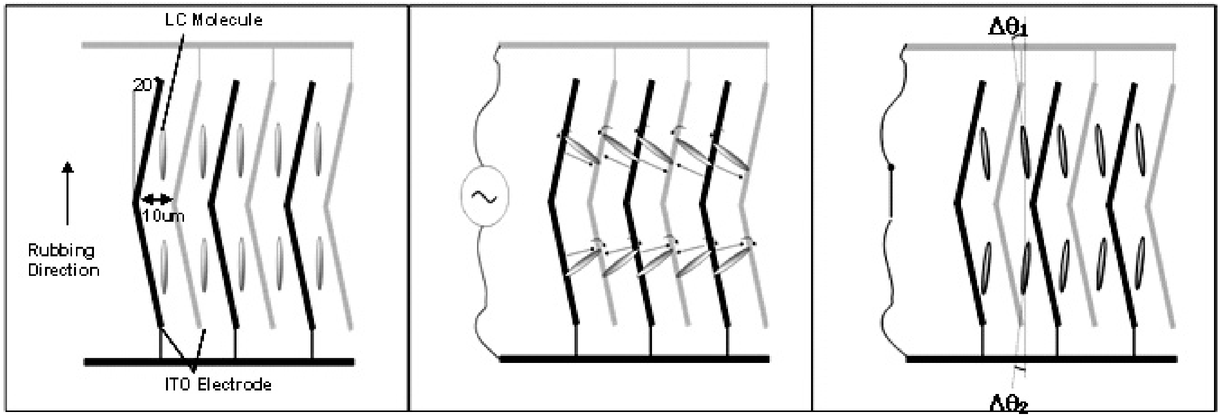

FIGURE 1 — Measurement scheme.

area of the substrate, and both of the glass substrates were assembled by curing under mechanical pressure in a heat chamber for 3 hours at 150°C. A positive-type LC mixture (Merck ZLI4792) was injected into the assembled cells in vacuum. The injection hall was end-sealed with UV sealant and we processed the cells at 110°C in a heat chamber for 30 minutes to align the LC molecule along the rubbing direction.

Figure 1 also describes the measurement scheme used in this work. The left part of Fig. 1 shows the initial state after preparing the samples. The rubbing direction is from the bottom to the top. LC molecules shown in the figure align along the rubbing direction. The middle part of Fig. 1 shows the state under AC driving. For these bended-comb-teeth ITO electrodes, the twist direction of the LC molecule along the electric field on the upper electrode area is always opposite the direction of the lower electrode area. The right part of Fig. 1 shows the slightly deviated LC molecules from the initial state after a long period of AC driving. It is easy to measure the exact deviation of the LC molecule by adding the difference in the deviations of the upper and lower electrode areas because the direction of the deviation is opposite to each other.

The black brightness was measured with an LCD analyzer (Meiryo Technica LCA-LU4A10) after driving by an AC square-wave electric field, the amplitude and frequency of which were ±10 V and 60 Hz, respectively. We obtained the LC director deviation angle $\Delta\theta = \Delta\theta_1 + \Delta\theta_2$, where $\Delta\theta_1$ and $\Delta\theta_2$ are, as indicated by right-hand figure of Fig. 1, the deviation angle calculated from the black brightness, respectively, of the lower and upper areas of the bended electrode. The electrodes connected to the function generator were shunted during the measurement to prevent static electric voltage.

An example of the measurement of the black brightness is shown in Fig. 2. We measured the exact black brightness under the cross-nicole polarized condition on both electrode areas. It is obtained as a function of the rotation angle φ of the set of cross-nicole polarizers. We denote φ giving the minimum brightness for the upper and lower areas by φ_U and φ_L, respectively. $\Delta\theta$ was calculated by

$$\Delta\theta = \varphi_U - \varphi_L. \tag{1}$$

Figure 2 was obtained by measuring the brightness data for 11 points every 0.1° for a 1° range under the cross-nicole condition. After plotting data, it was approximated by a quadratic curve. We calculated the darkness points φ_U and φ_L by fitting the measurement data. The accuracy of φ_U and φ_L was better than 0.02°.

In the initial state, at first, we calculated $\Delta\theta$ for each sample. Each of the initial values of $\Delta\theta$ was confirmed to be almost zero. It was less than 0.02°. We monitored the change of $\Delta\theta$ for about 1 month under AC driving. For one measurement, the sample cell was temporally removed from the AC driving circuit and put into the LCD Analyzer with shunting electrodes. After measurement, the sample cell was put under the AC driving circuit again to continue the experiment.

After finishing long-term AC driving, we also monitored the decay of $\Delta\theta$. For that case, the electrodes of all the samples had been kept shunted at room temperature for the entire period of the measurement and annealing processes.

3 Results and discussions

Results depending on the period of AC driving for various pile impressions and bake-temperature conditions are

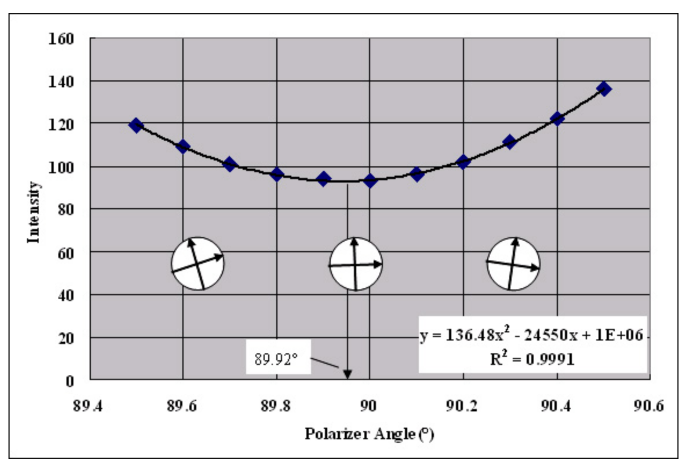

FIGURE 2 — Example of measurement data.

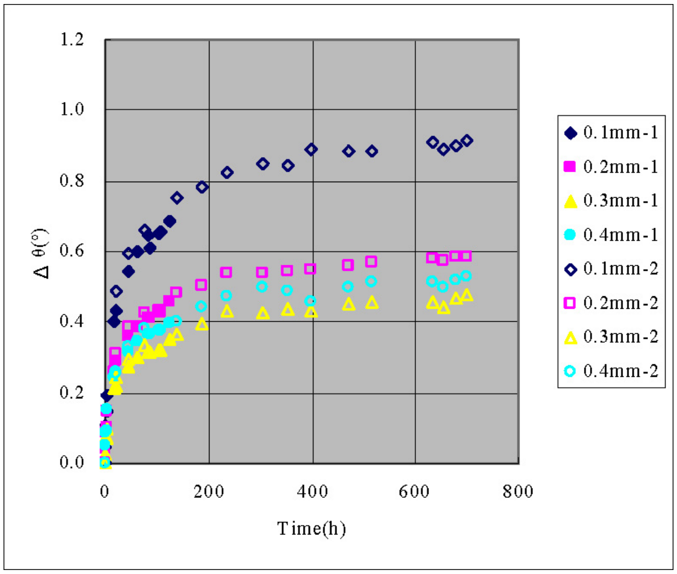

FIGURE 3 — Δθ dependence on pile impression during AC driving (bake temperature, 230°C).

shown in Figs. 3 and 4. We used hour as the unit of time. We performed experimental cycle two times for the same sample. For the first cycle, we measured for 170 hours and for the second cycle, we measured for 700 hours under a long period of AC driving. The closed symbols show the first set of data and the open symbols show the second set of data for both Figs. 3 and 4. It is interesting that each Δθ continued to increase slowly and step by step, depending on the AC driving period. Comparing the first-cycle with the second-cycle data of Figs. 3 and 4, we confirmed that the first and the second sets of data showed good agreement. It also became clear that our measurement method had good reproducibility. Δθ indicated a different saturation value, depending on conditions.

Figure 3 indicates that the saturation of Δθ changed depending on the pile impression. In other words, it changed depending on the rubbing strength. In IPS mode, strong rubbing was one of useful methods to prevent an increase in the Δθ value. However, in case of a pile impression of 0.4 mm, improvement was not obtained compared with 0.3 mm. This indicates a limit of improvement when using a strong rubbing method.

Figure 4 indicates that Δθ also depends on the post-bake temperature. The “Skipped” condition is for the case in which the post-bake process was skipped; *i.e.*, there was no post-bake process. It was indicated that the post-bake process is important in preventing Δθ from increasing. But increasing the post-bake temperature showed saturation at decreasing Δθ. This also shows that there is a limit in improvement by means of the tuning post-bake-process condition.

Figures 5 and 6 show the relaxation of the Δθ value after a long period (170 and 700 hours) of AC driving. It is interesting that Δθ decreased so slowly, and the Δθ value was saturated and did not return to zero which was the initial position before application of an AC field. It implies an irreversible plastic deformation that imposes a memory on Δθ. The relaxation time of converging Δθ was typically on the order of 100 hours. We expected that this memory effect was caused from the conformation change of the PI surface molecules affected by the torque from the LC molecules during AC driving.

We confirmed that the annealing process at 110°C for 3 hours after the relaxation of Δθ reset Δθ to initial zero for all samples; the 110°C is much less than the glass-transition temperature of bulk PI and higher than the nematic isotropic point temperature of ZLI4792. We expect that the memory effect involves rheological deformation of the PI surface.

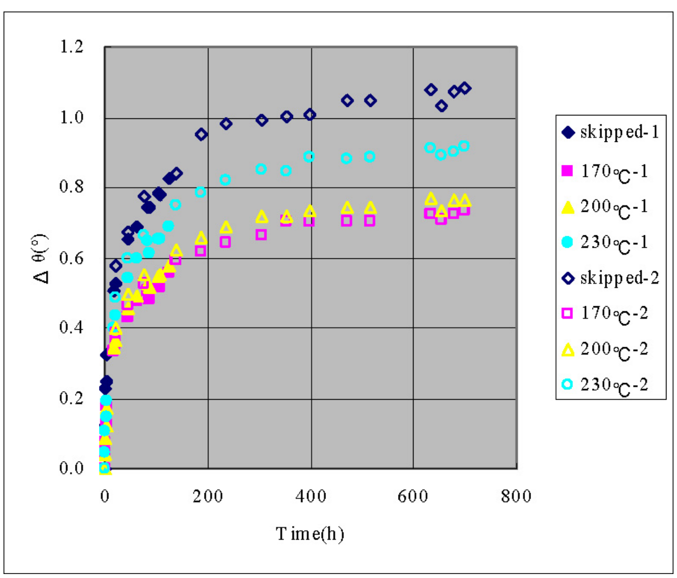

FIGURE 4 — Δθ dependence on post-bake temperature during AC driving (pile impression, 0.1 mm).

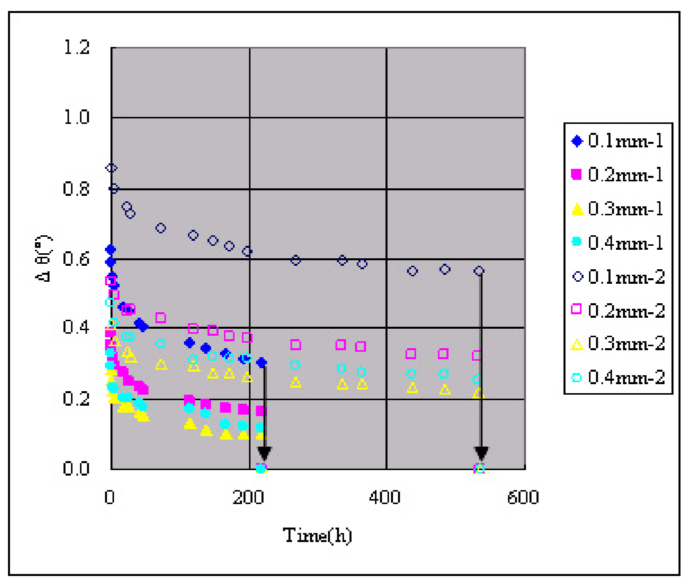

FIGURE 5 — Relaxation of Δθ dependence on pile impression (bake temperature, 230°C).

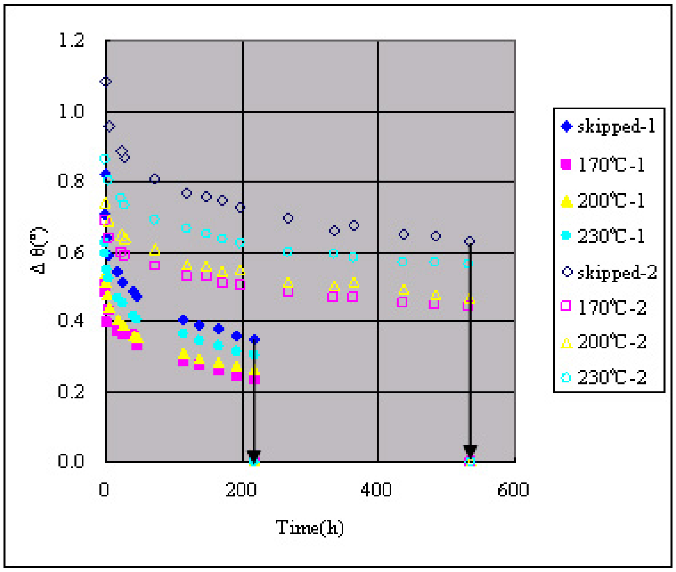

FIGURE 6 — Relaxation of Δθ dependence on post-bake temperature (pile impression, 0.1 mm).

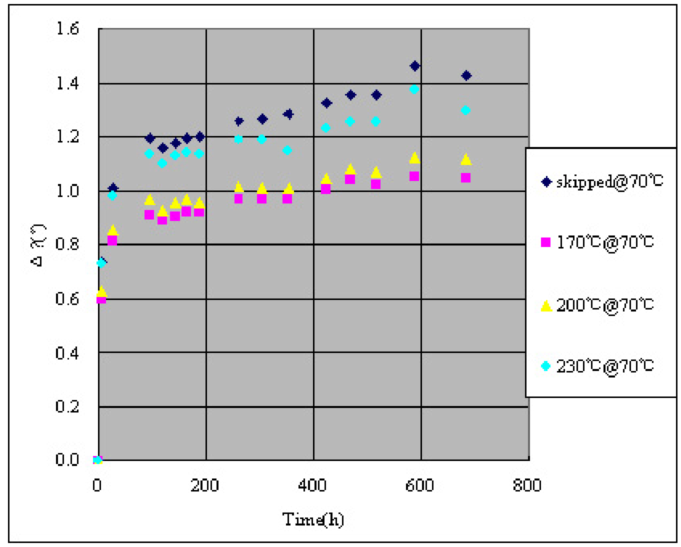

FIGURE 8 — Δθ dependence on post-bake temperature during AC driving at 70°C (pile impression, 0.1 mm).

PI films mainly have a main-chain structure without a network structure. It is reported that the surface main-chain structure of benzene rings is aligned along the rubbing direction, and the liquid-crystal-molecule alignment layer thickness is about 10 nm.[4] The LC molecule is aligned along the rubbed PI surface. Long-term AC voltage driving causes torque from the twisted LC molecules. We consider that the main factor that induces the memory effect of the deviation between the LC molecules and the rubbing direction is the rheological deformation of the aligned PI surface of a 10-nm thickness.

The methods of anchoring strength measurement between the LC molecules and the PI surface have been in development for decades. It has been considered that strong anchoring between the LC molecules and the PI surface is the most important factor in improving the IPS contrast problem. However, even if the ideal strong anchoring would be achieved, torque-induced deformation of the PI surface would induce a reduction in contrast. We conclude that the surface rheological phenomena of the PI alignment film are one of the most important factors for the contrast-reduction problem.

Figures 7 and 8 show that Δθ depends upon the period of AC driving in a heat chamber at 70°C, which is lower than the nematic isotropic temperature of ZLI4792. Both figures show that high temperature accelerates the increase in Δθ. This reason is explained by considering that the PI surface molecules of a main-chain structure move more easily in high temperature than at room temperature. We insist that this is related to the time–temperature superposition rule which is familiar in polymer rheology. It should be noted that the Δθ value for all conditions had an increasing ten-

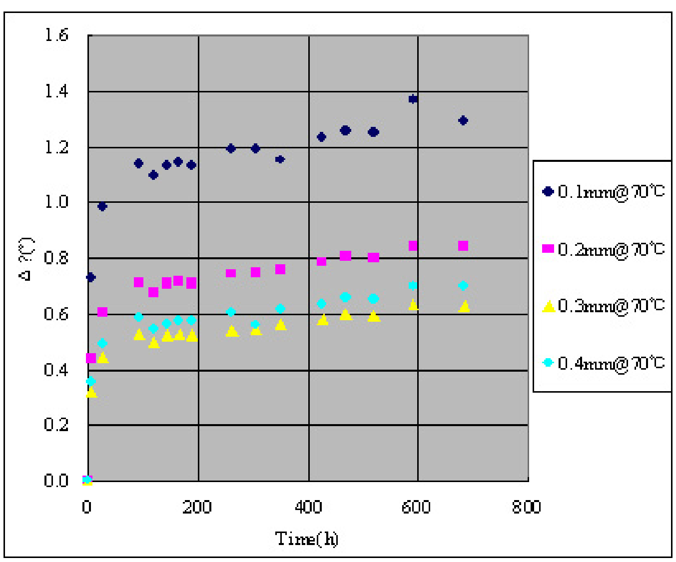

FIGURE 7 — Δθ dependence on pile impression during AC driving at 70°C (bake temperature, 230°C).

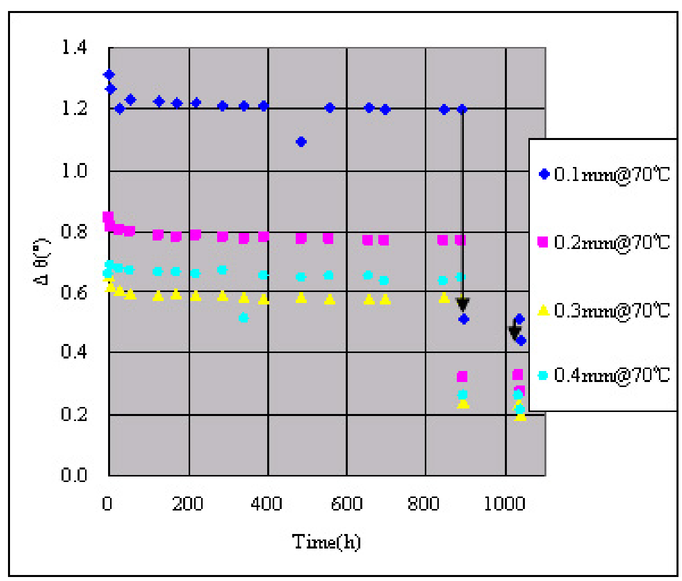

FIGURE 9 — Relaxation of Δθ dependence on pile impression after AC long-term driving at 70°C (bake temperature, 230°C).

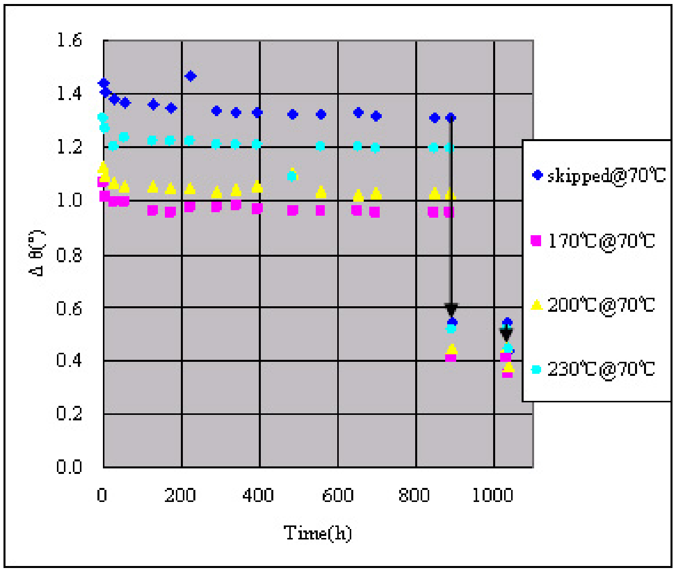

FIGURE 10 — Relaxation of Δθ dependence on post-bake temperature after AC long-term driving at 70°C (pile impression, 0.1 mm).

dency without saturation. We consider that acceleration by temperature supports our model of rheological deformation of the aligned PI surface molecules.

Figures 9 and 10 show that the relaxation of Δθ at room temperature after a long period of AC driving in a heat chamber at 70°C. Compared with Figs. 5 and 6, it is shown that the relaxation magnitude for all conditions becomes small. After 800 hours as the relaxation period elapsed, we also performed the annealing process on the accelerated samples at 110°C for 3 hours. It is so interesting that for all experimental conditions, the Δθ value decreased to a finite value which was non-zero. A few days later, we performed the annealing process again, but each Δθ did not result in a substantial change with a dramatic approach to zero. These results show that PI surface molecules with a main-chain structure transformed over the elastic limit by a long period of AC driving in a heat chamber at 70°C.

Several papers reported on models of the memory effect.[1–3] For example, Suzuki *et al.* estimated the desorption and readsorption of LC molecules on the PI surface.[1]

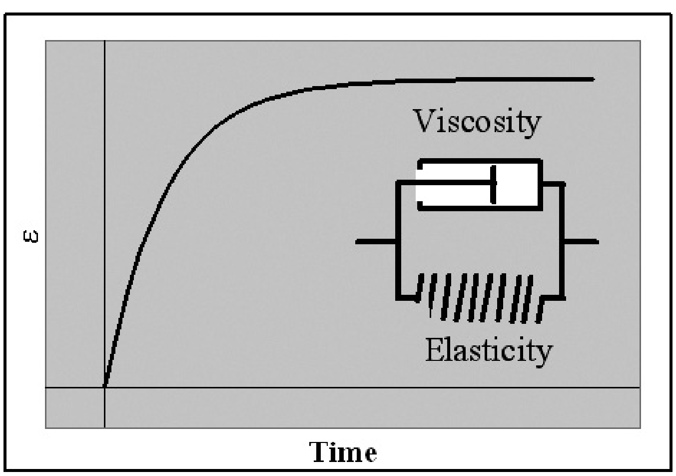

FIGURE 11 — Concept of Kelvin–Voigt model.

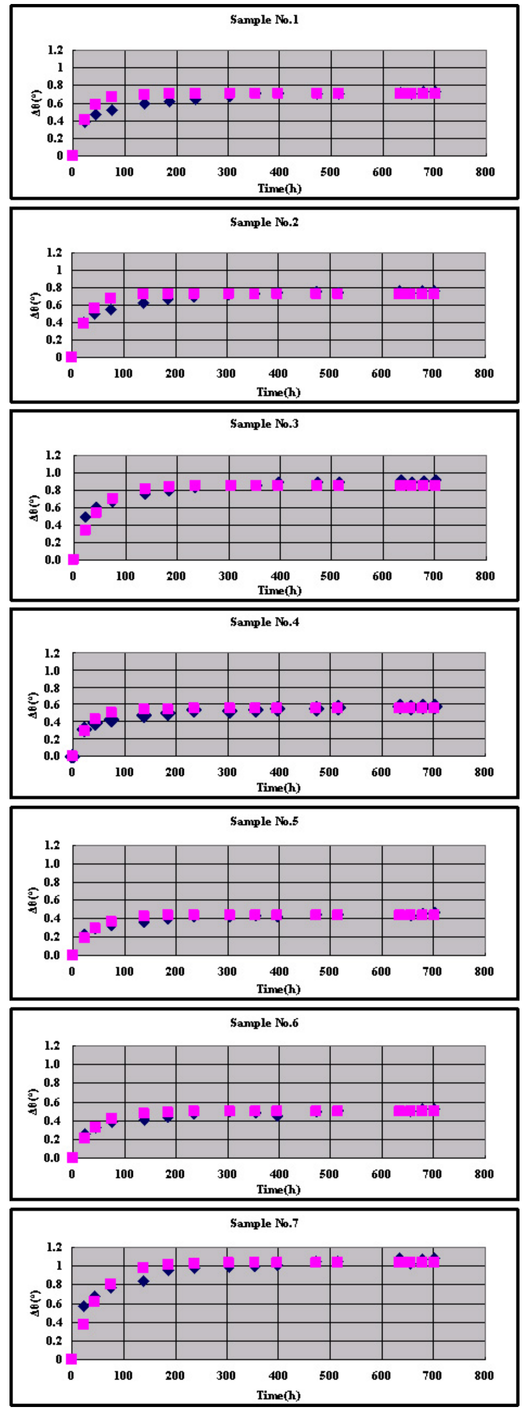

FIGURE 12 — Comparison of the plots of Δθ measurement data and calculated data by using the Kelvin–Voigt Formula.

And Yamaguchi *et al.* on the TN mode observed the reorientation of the surface molecules of PVAC (polyvinylacetate).[3] We consider our present results were also based on a change in the PI molecules.

By considering these results, we expect that AC image sticking is mainly the problem of the PI surface rheology. We adopted one well-known rheology model called the Kelvin–Voigt (KV) model to explain and confirm the rheology of the polymer transformation of the PI surface. The KV model is a simple model involving the parallel arrangement

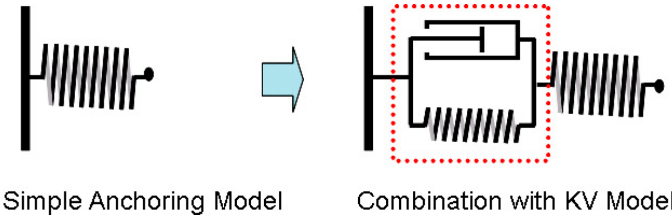

FIGURE 13 — Concept of combination of azimuthal anchoring and Kelvin–Voigt model.

of a dashpot representing viscosity η and a elastic spring constant of Young's modulus E. Figure 11 describes the KV model, which is used to explain the creep phenomenon of strain $\varepsilon(t)$ for time t under constant stress σ. Thus, $\varepsilon(t)$ is expressed by

$$\varepsilon(t) = (\sigma/E)\,[1 - \exp(-t/B)], \tag{2}$$

where $B = \eta/E$.

Figure 12 shows both our measurement and calculated data by the KV model for all experimental conditions. ε was replaced by Δθ in the present case. The measurement data agrees well with the calculated data for any sample number in Figs. 3 and 4. These results by using the KV model support the correctness of our conclusion that PI surface rheology is important.

By summarizing these results, we consider that the deviation of the LC director from the rubbing direction during long-term AC driving in IPS mode is mainly caused by the PI surface rheology. We tried to combine the azimuthal anchoring model between the LC molecule and the PI surface with the rheology model on the PI main-chain structure.

Figure 13 shows the difference between the simple anchoring model and the present KV model. In the case of azimuthal anchoring measurement by using the strong-voltage method,[5] the spring is stretched by deforming the LC under an electric field. On the other hand, if we consider the surface rheology, the spring and the dashpot for the KV arrangement is stretched by the LC spring torque. These two models cause different situations.

Figure 14 shows an illustration for both cases of simple anchoring and the present model for the KV system. The left side of Fig. 12 shows the initial situation where the LC molecules are homogeneously aligned along the rubbing direction. For the azimuth anchoring measurement, the measurement method using a strong voltage was proposed.[5] According to the paper, more than 100 V is required to measure the anchoring energy. The application of a strong voltage is so short that the deviation is mainly an azimuthal anchoring factor not causing surface deformation as is illustrated for case 1 in Fig. 14.

For AC long-term driving, a smaller voltage is applied for a long period so that the PI surface deforms showing rheological relaxation as is illustrated for case 2 in Fig. 14. After AC long-term driving, Δθ slowly recovers, hindered by the dashpot viscosity effect. When the deviation exceeds the limit of elastic deformation, the recovery to initial zero will not be completed.

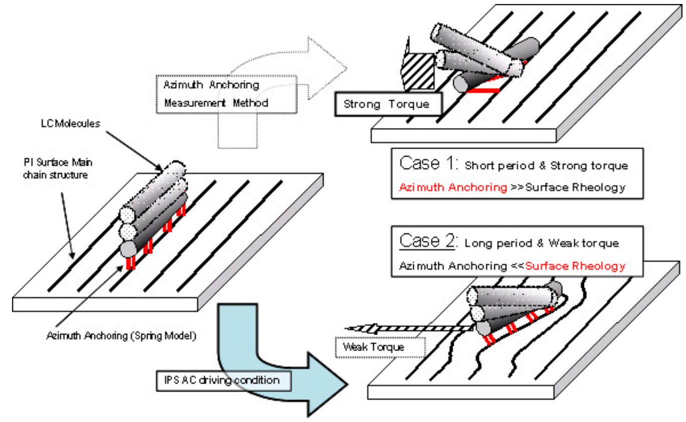

FIGURE 14 — Deviation explanation scheme of azimuthal anchoring and Kelvin–Voigt Model between LC molecules and PI surface.

By placing samples at 110°C in a heating chamber, a decrease in the viscosity of the dashpot can lead the recovery to zero easily. But in the case of acceleration at 70°C for AC long-term driving, the stretch is more than the limit of reversible elasticity and the deviation does not recover to zero even if we put samples under 110°C conditions.

It is considered thus far that strong azimuthal anchoring is one of the most important factors in reducing the AC image-sticking problem of the IPS mode. But based on our results and consideration, it is finally concluded that a surface rheology at a depth of about 10 nm is a more important factor than strong azimuthal anchoring in improving the AC image-sticking problem in the IPS mode. This direction is important in developing new PI material.

We have been developing new PI material based on the view point of surface rheology, and it is indicated that a type of new PI material can remarkably reduce the AC image-sticking problem. It is confirmed that our direction is correct and useful for the improvement in LCD quality for the AC image-sticking problem.

4 Summary

We examined the efficiency of the measurement of the deviation Δθ of the LC director from the rubbing direction as an evaluation method of the image-sticking problem. To improve the contrast decrease in the IPS mode after long-term AC driving, we did not find that tuning the process conditions, such as rubbing pile impression and post-bake process, was sufficient. According to our analysis and consideration of the measured results of Δθ, we proposed that the memory phenomenon was caused by small rheological deformation of the surface molecular conformation of PI.

By considering the mechanism of the rheological deformation, we tried to use the KV model. Finally, we considered a new model to combine azimuthal anchoring with the KV model for the LC molecules and main-chain structure of the PI surface. This gave us a new direction for developing a new PI material to improve the AC image-sticking problem of the IPS mode.

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