Relation between Monomer Structure and Image Sticking Phenomenon of Polymer-Sustained-Alignment Liquid Crystal Displays

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Relation between Monomer Structure and Image Sticking Phenomenon of Polymer-Sustained-Alignment Liquid Crystal Displays

Yohei Nakanishi*, Kazutaka Hanaoka, Masakazu Shibasaki, and Kenji Okamoto

Sharp Corporation, Tenri, Nara 632-8567, Japan

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We investigated the image-sticking phenomenon of polymer-sustained-alignment liquid crystal displays (PSA-LCDs) by the evaluation of residual DC and the difference in tilt angle. Experimental results indicate that the difference in tilt angle affects the image sticking of PSA-LCDs more than the residual DC. We also found that the difference in tilt angle is strongly dependent on the chemical structure of the monomer that forms the polymer layer between the alignment layer and the liquid crystal layer by photopolymerization.

1. Introduction

Active-matrix-type liquid crystal displays (AM-LCDs) are the most popular type of flat-panel display and are used in television sets, notebook computers, cellular phones, personal digital assistants, handheld video game machines, digital signage, and so forth, because they have features such as high resolution, low power consumption, and thinness. So far, AM-LCDs have usually used a twisted nematic (TN) mode,[1] but the TN mode has a disadvantage of narrow viewing angle characteristics. Therefore, other modes with wide viewing angle characteristics such as in-plane switching (IPS) mode,[2] fringe-field switching (FFS) mode,[3] multidomain vertical alignment (MVA) mode,[4] and patterned vertical alignment (PVA) mode[5] have been developed. Among these modes, vertical alignment (VA) modes such as the MVA and PVA modes have a very high contrast ratio because liquid crystal (LC) molecules vertically aligned by the alignment layers cause little retardation. However, the low transmittance of these VA modes is disadvantageous because they use protrusions or slits of pixel electrodes to control LC molecules, which cause a decrease in transmittance. A polymer-sustained-alignment (PSA) technology with a pixel structure of minutely patterned indium tin oxide (ITO) (Fig. 1), which was developed by our group, had high transmittance because the additional polymer layer on each alignment layer sustained the alignment of LC molecules instead of the protrusions or the slit of pixel electrodes, which decrease the transmittance.[6] This additional polymer layer was made by polymerization of the monomer included in the LC by the irradiation of UV light.

Another important problem that must be solved is the image-sticking phenomenon, where an image is still visible after it is no longer addressed. Image sticking is generally explained by the generation of residual direct current (DC) voltage (V_{rdc}), which is a DC offset voltage generated inside an LC cell by a DC offset voltage applied externally.[7] However, in the case of PSA-LCDs, V_{rdc} is sufficiently small for serious image sticking to be avoided. Therefore, we had to consider other possible causes of image sticking. It is well known that LC molecules are stressed by an electric field when the director of the LC and the line of electric force are at an angle of more than 0°. LC molecules on the substrates of MVA or PVA mode LCDs align vertically on the substrates and are not stressed by an electric field normal to the substrate, but the LC molecules on the substrates of a PSA-LCD, which align at an angle of less than 90°, are stressed by an electric field. This consideration leads us to focus on the difference in tilt angle as the cause of image sticking.

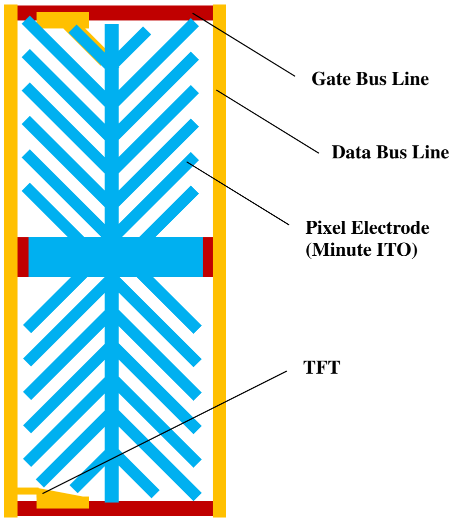

Fig. 1. (Color online) Pixel structure of PSA-LCD.

We fabricated thin-film transistor (TFT) type LCDs using PSA technology to evaluate the image-sticking phenomenon of the LCDs and found that the cause of the phenomenon cannot be explained by residual DC. In this paper, we investigated the image-sticking phenomenon of PSA LCDs and demonstrated the solution to this problem.

2. Experiment

2.1 Materials

The LC material used in this study is a negative-type LC material whose dielectric anisotropy ($\Delta\varepsilon$) is -3.8 and birefringence (Δn) is 0.0822. The chemical structures of the monomers are shown in Fig. 2(a)–2(c). Monomer A shown in Fig. 2(a) is 1,4-bis{4-[3-(acryloyloxy)propyloxy]benzoate}-2-methylpropane, monomer B [Fig. 2(b)] is 4,4′-bis[6-(acryloyloxy)hexyloxy]-1,1′-biphenylene, and monomer C [Fig. 2(c)] is 4,4′-bis(acryloyloxy)-1,1′-biphenylene. Each monomer was dissolved in the LC material. The photoinitiator Irgacure 651 (from BASF) was also dissolved in each LC material. A polyimide is also used to align the LC molecules vertically.

*E-mail address: nakanishi.yohhei@sharp.co.jp

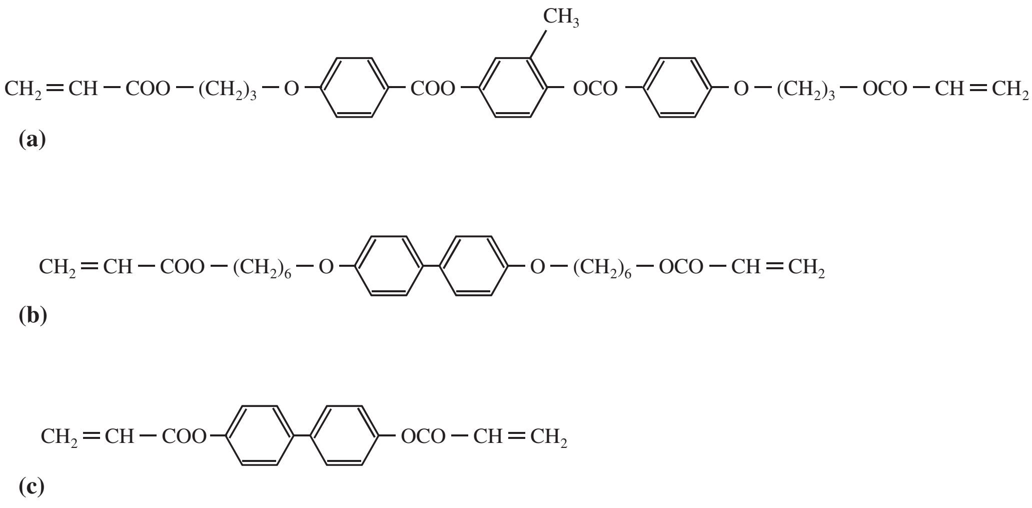

Fig. 2. Molecular structure of monomers. (a) 1,4-bis{4-[3-(acryloyloxy)propyloxy]benzoate}-2-methylpropane, (b) 4,4′-bis[6-(acryloyloxy)hexyloxy]-1,1′-biphenylene, and (c) 4,4′-bis(acryloyloxy)-1,1′-biphenylene.

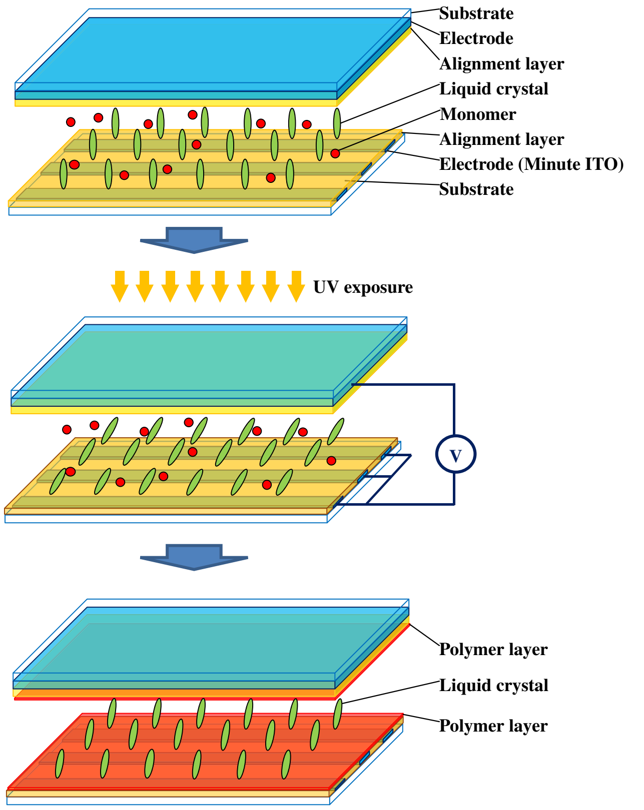

Fig. 3. (Color online) Fabrication process of polymer layer of PSA-LCD.

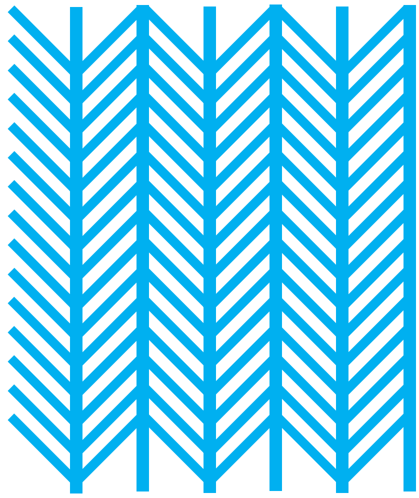

Fig. 4. (Color online) Pixel structure of test cell used to determine ΔT.

2.2 Preparation of LC cells

The PSA-LCD cells were fabricated as shown in Fig. 3. The TFT cells we used for study had a VA polyimide film on the substrates and negative-type LC doped with 0.3 wt% of one of the monomers and the photoinitiator between the substrates. The LC molecules were aligned vertically on the polyimide films of the cells when a voltage of 0 V was applied. A voltage of 10 V DC was applied to the cells, which were left until the alignment of the LC became stable. Then the cells were exposed to UV light of 4 J/cm^2 at room temperature to polymerize the monomer. To analyze the image-sticking phenomenon easily, we fabricated two types of simple cells whose substrates had ITO layers and VA films. The first type was an antiparallel cell in which VA films were rubbed and the pixel size was 1×1 cm^2. The negative-type LC material doped with 0.3 wt% of each monomer and the photoinitiator were injected between the substrates. A voltage of 10 V DC was applied to the cells and the cells were left until the alignment of the LC molecules became stable. Then the cells were exposed to UV light of 4 J/cm^2 at room temperature to polymerize each monomer. We used the antiparallel cells to measure Δtilt, which is determined later. The second type was a VA cell with pixels in which one of the substrates had a zigzag patterned ITO layer (Fig. 4) modeled on TFT electrodes, and the other substrate had an ITO layer with no pattern. Polarizers were placed orthogonally on each substrate of this cell to prevent the leakage of light without applying a voltage. We used the second type of test cell to measure ΔT, which is determined later.

2.3 Determination of image sticking

To examine the image-sticking phenomenon quantitatively, we defined the image-sticking ratio R_{is} as follows.

A black and white checker pattern was displayed for 48 h in each TFT cell prepared by us. Thereafter, the halftone 46/255 was displayed in the whole display region. The brightness B_w in the region that previously displayed white and the brightness B_b in the region that previously displayed black were measured, and the difference between B_w and B_b was divided by B_b. That is, the image-sticking ratio (R_{is}) was calculated using the following equation:

$$R_{is} = \frac{B_w - B_b}{B_b} \times 100\ (\%). \tag{1}$$

2.4 Residual DC

The residual DC (V_{rdc}) values were measured by the flicker minimum method reported previously[7] using the antiparallel cells. A DC offset voltage of 0.5 V was applied for 2 h at 50 °C to each antiparallel cell in order to apply stress.

2.5 Determination of Δtilt

We also used the antiparallel cells to measure Δtilt. After polymerization by UV light irradiation, a square-wave voltage of 20 V without a DC offset voltage was applied to each antiparallel cell for 20 h in order to apply stress. We determined Δtilt as the difference in the tilt angle of the LC before and after applying stress, i.e.,

$$\Delta\mathrm{tilt} = \mathrm{tilt}_1 - \mathrm{tilt}_0, \tag{2}$$

where tilt_0 is the tilt angle before applying stress and tilt_1 is the tilt angle after applying stress (Fig. 5).

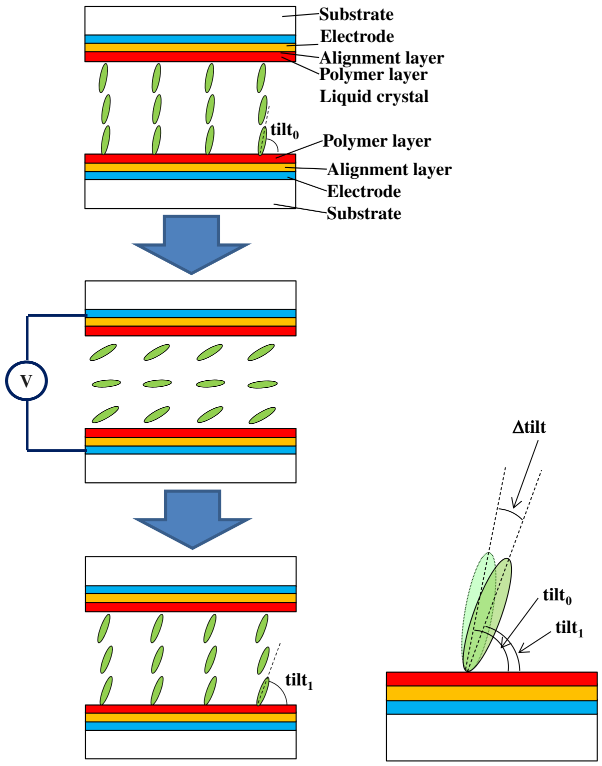

Fig. 5. (Color online) Determination of Δtilt.

Table I. R_{is} (%) for each monomer.

A	B	C
25	26	6

2.6 Determination of Δ*T*

We used the second type of test cells to determine ΔT. After polymerization by UV light irradiation, a square wave of 20 V without a DC offset voltage was applied to each cell for 20 h in order to apply stress. We determined ΔT as follows:

$$\Delta T = \frac{T_1 - T_0}{T_0} \times 100\ (\%), \tag{3}$$

where T_0 is the transmittance measured at the voltage corresponding to the halftone 46/255 at $\gamma = 2.4$ before applying stress and T_1 is the transmittance measured at the same voltage after applying stress. ΔT is the difference in the transmittance of the cell before and after applying stress divided by the transmittance before applying stress.

3. Results and Discussion

The image-sticking ratios R_{is} of the PSA-LCDs with monomers A–C are summarized in Table I. The results indicate that the degree of image sticking for the PSA-LCD with monomer C is much smaller than those of the PSA-LCDs with monomers A and B. This shows that the image-sticking ratio is strongly dependent on the monomer that forms the polymer layer of the PSA-LCD.

There are many reports that residual DC affects the image sticking of conventional LCDs.[7–11] The generation mechanism of image sticking due to a residual DC is as follows. If a symmetrical square wave is applied to an LC cell with a residual DC, the LC cell appears to flicker because an asymmetric square wave, which is the sum of the externally applied voltage and the residual DC voltage, is applied to the LC layer of the LC cell as shown in Fig. 6. After a pattern is addressed on the LCD, part of the screen with the residual DC appears to flicker and the other part without residual DC

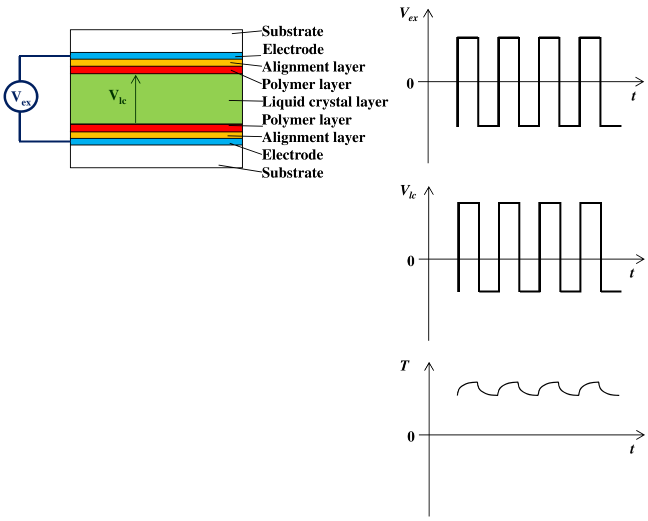

Fig. 6. (Color online) Residual DC and flicker of the LCD.

Table II. Common sweep and V_{rdc} (mV) for each monomer.

	A	B	C
Common sweep	No reverse	No reverse	No reverse
V_{rdc}	<30	<30	<30

does not appear to flicker, even though the gray scale is addressed to the whole area of the LCD. The flickering area is brighter than the other area; thus, the pattern is still visible even though the other pattern is addressed on the LCD.

When the voltage of the common electrode is swept to eliminate the residual DC, the flicker becomes weaker and finally cannot be perceived. If the flicker level is the same over the whole area of the LCD, no image sticking should be observed. If the voltage of the common electrode is swept further, one can observe reverse image sticking, where the part without residual DC is brighter than the part with residual DC. We used this "common sweep technique" to determine whether or not the cause of the image-sticking phenomenon for PSA-LCDs is residual DC. We found that reverse image sticking could not be observed for all the PSA-LCDs with monomers A–C. This indicates that the larger image-sticking ratios R_{is} obtained for the PSA-LCDs with monomers A and B are not due to the residual DC. In order to confirm the results, we also evaluated V_{rdc} for the antiparallel cells by applying the DC offset voltage described above. The results for V_{rdc} are listed in Table II; V_{rdc} was below 30 mV for all antiparallel cells with monomers A–C. V_{rdc} is reported to be proportional to the externally applied DC offset voltage,[7] and we empirically found that image sticking is not observed when V_{rdc} is below 30 mV under our measurement conditions. These results indicate that the cause of the image-sticking phenomenon for PSA-LCDs is not explained by the residual DC, leading us to focus on other possibilities. For instance, the cell gap, the birefringence of the LC, and the applied voltage were all fixed over the whole area of the displays, and hence they could not have caused image sticking. Therefore, we focus on the differences in the tilt angle before and after applying the rectangular voltage (Δtilt) to the PSA-LCDs because the polymer layers, which are formed by the polymerization of monomers A–C, are in direct contact with the LC layer and control the tilt angle of the LC molecules.

Figure 7 shows the Δtilt values for the antiparallel cells of monomers A–C. The results are strongly dependent on the monomer that forms the polymer layers. In particular, Δtilt for the antiparallel cell of monomer C is much smaller than those for the antiparallel cells of monomers A and B. This tendency approximately corresponds to the result for R_{is} evaluated using the TFT panels of PSA-LCDs, indicating the possibility that the appearance of image sticking for the PSA-LCDs is derived from the generation of a nonzero Δtilt due to the application of a rectangular voltage, not a DC offset voltage. In order to verify this, the evaluation of the difference in transmittance before and after applying the rectangular voltage without the DC offset voltage (ΔT) is necessary for the PSA-LCDs of monomers A–C. However, using the TFT panels, it is too complicated to analyze the phenomenon of image sticking directly because the actual voltage applied to the LC layer is determined by not only the

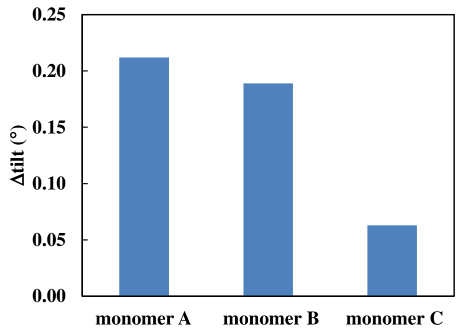

Fig. 7. (Color online) Results for Δtilt.

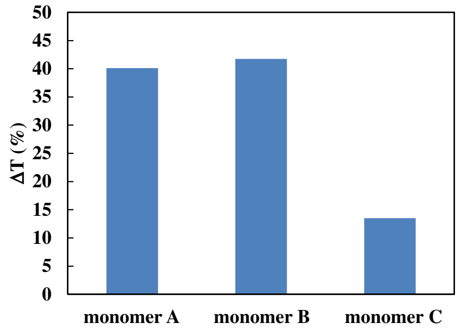

Fig. 8. (Color online) Results for ΔT of test cells.

signal of the data bus-lines but also the capacitive coupling between the many electrodes such as the source and drain of the TFT or the bus-line and the pixel electrodes. To observe image sticking on the pixel electrodes, we used the second type of test cells described above, which are simple cells with quasi-TFT panel pixels. The ΔT values were determined as depicted in Fig. 8. The result for ΔT is also dependent on the monomer and the tendency is comparably close to the results for Δtilt and R_{is}. The ΔT value for the antiparallel cell of monomer C is much smaller than those for the antiparallel cells of monomers A and B. These results indicate that the image sticking of PSA-LCDs is induced by the difference in tilt angle due to the application of a rectangular voltage.

It is significant that Δtilt for monomer C is much smaller than those for monomers A and B because the PSA-LCD with monomer C shows little image sticking. This phenomenon is explained by the molecular structure of the monomers. Monomers A and B have flexible alkyl chains between the phenylene core and the functional group. Moreover, monomer A has an ester bond between the phenylenes. The alkyl chains and ester bond enable it to change its conformation easily, and it can have multiple conformations because a single bond between carbon atoms can rotate freely.[12] When a rectangular wave voltage was applied to the PSA-LCD, the LC molecules realigned owing to the electrostatic energy induced by the application of a rectangular voltage and the elastic energy of the LC molecules, and stress was applied to the polymer layer between the alignment layer and the LC molecules owing to the elastic energy of the LC molecules. The flexible alkyl chains and the ester bond in the monomer could change their conformations owing to the stress and thus slightly modify the polymer layer, and consequently induce the generation of a nonzero Δtilt. In contrast, the functional groups of monomer C bonded directly to the phenylene core, and hence it hardly caused any change in its conformation. Therefore, monomer C had a small Δtilt, resulting in the comparably small ΔT and R_{is}.

4. Conclusions

We investigated image sticking of PSA-LCDs and clarified that it is caused by the difference in tilting angle not by the residual DC. We also discovered that a monomer whose core biphenyl group bonds directly to the polymerizable acrylate group had a small Δtilt. This monomer reduced the image sticking of PSA-LCDs, making the commercial production of PSA-LCDs possible.

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