INVITED PAPER *Special Section on Electronic Displays*

A Mechanism of Short-Term Image-Sticking Phenomenon Caused by Flexoelectric Effect in IPS LCD

Daisuke INOUE[†a)], **Tomomi MIYAKE**[†], *and* **Mitsuhiro SUGIMOTO**[†], *Nonmembers*

SUMMARY We propose a novel mechanism of short-term image-sticking phenomenon in in-plane switching liquid crystal displays (IPS LCDs) that is related to ionic relaxation generated by a vertical electric field caused by a flexoelectric effect. We discuss the differences between electric fields caused by the flexoelectric effect and those caused by DC bias voltage.

key words: *IPS, image-sticking, flexoelectric effect, ionic relaxation*

1. Introduction

Liquid crystal displays (LCDs) have been used in various devices, including TVs, monitors, tablets and smart phones; however, there are still some unresolved issues regarding image quality. One of these issues is the image-sticking phenomenon, in which a previous image remains visible when the next image is displayed.

Residual DC (RDC) voltage common in other LCD modes (such as twisted nematic (TN) mode) and AC image sticking caused by an easy-axis change from an initial position are well known as the main factors that affect image-sticking phenomena in in-plane switching (IPS) mode [1].

We can separate image sticking caused by RDC and an easy-axis change by following the method below [2]. VT curve simulation results are shown in Fig. 1, in which positive and negative voltages were equal without RDC and unequal with RDC +300 mV. If RDC was generated, transmittance at low voltage increased and transmittance at high voltage decreased because the change in the VT curve monotonically increases and decreases at low and high voltages, respectively. As image sticking is usually evaluated at low voltage when positive and negative voltages become asymmetrical, if RDC is generated, an increase in transmittance occurs, and if the Vcom voltage is changed, transmittance at low voltage increases for the same reason.

As shown in Fig. 2, transmittance dependency of the Vcom voltage made a quadratic curve. When RDC was generated, the quadratic curve shifted horizontally, and when AC image sticking occurred, it shifted vertically.

In addition, as mentioned in [1], AC image sticking is considered irreversible because it is caused by an easy-axis change. However, we confirmed the existence of a different image-sticking phenomenon that was not caused by RDC or AC image sticking but was similar to AC image sticking aside from an early-recovery property. We found a relationship between this short-term image-sticking phenomenon and internal vertical electric fields due to the flexoelectric effect [3]. We detail the differences between the electric fields caused by the flexoelectric effect and those caused by DC bias voltage.

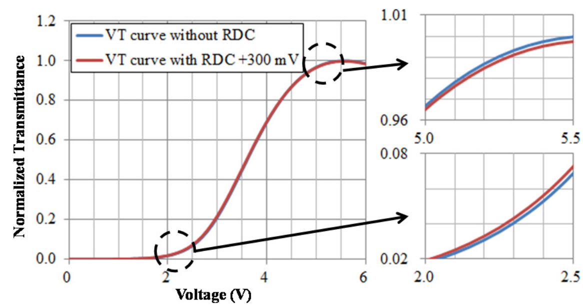


Fig. 1 VT curves without RDC and with RDC of +300 mV. Simulated by LCD Master.

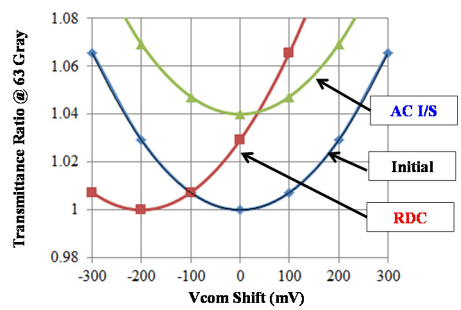


Fig. 2 Transmittance dependency of Vcom voltage before and after aging period.

2. Measurement and Simulation

2.1 Measurement Method of Short-Term Image Sticking Phenomenon

To observe the image-sticking phenomenon, we used IPS cells filled with positive nematic liquid crystal (LC), as shown in Fig. 3. IPS cells having pixel and common electrodes on different layers are very strong resistant against short circuits between those electrodes, but there is a possibility of RDC generation due to the asymmetric structure between the pixel and common electrodes like that in FFS mode. So, we evaluated the RDC voltage during 255 Gray

Manuscript received February 26, 2018.
Manuscript revised May 31, 2018.
[†]The authors are with Tianma Japan, Ltd., Kawasaki-shi, 212–0058 Japan.
a) E-mail: d-inoue@tianma-jp.com
DOI: 10.1587/transele.E101.C.846

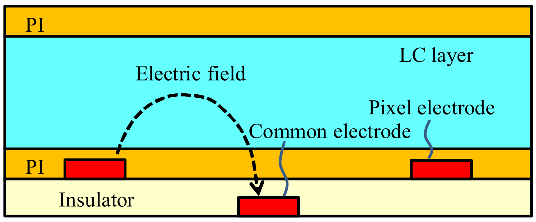


Fig. 3 Structure of IPS test cell.

Table 1 Measurement results of grayscale voltage in IPS cells.

Gray Level	AC voltage
63 Gray	2.8 V
127 Gray	3.4 V
191 Gray	4.0 V
255 Gray (White)	5.4 V
VT peak voltage	5.8 V

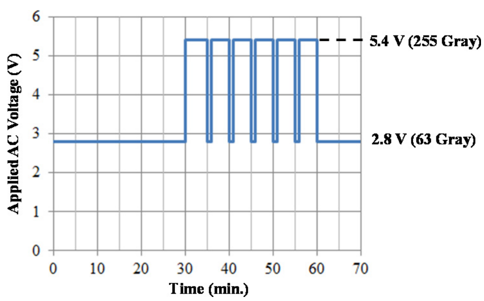


Fig. 4 Applied AC voltage image.

AC stress voltage application. When measuring the transmittance change of IPS cells, we used the color analyzer CA-210 by Konica Minolta, Inc., driven by a function generator with square waves.

We measured the VT curve to calculate each grayscale voltage as shown in Table 1. Grayscale was calculated to have a gamma value of 2.2.

Observation of the image-sticking phenomenon was carried out in accordance with the following procedure.

1. Apply 63 Gray voltage for 30 minutes to confirm transmittance stability.

Transmittance was measured every minute.

2. Apply AC stress voltage for 30 minutes to confirm image-sticking phenomenon.

Transmittance was measured every five minutes at 63 Gray voltage.

3. Apply 63 Gray voltage for 10 minutes to confirm transmittance recovery.

Transmittance was measured every ten seconds until one minute had passed and then measured every minute from 1–30 minutes.

An image of the applied AC voltage is shown in Fig. 4. When we measured the 0 Gray image-sticking phenomenon, we applied 0.01 [V], instead of 63 Gray voltage.

2.2 Measurement Method for Residual DC Voltage

During the observation of short-term image-sticking when using AC voltage, if a large residual DC voltage was generated, there was a possibility that it influenced short-term image-sticking. Therefore we measured residual DC voltage caused by AC voltage with the flicker-minimizing method [4]. When measuring RDC voltage, we used the same color analyzer and function generator used in previous measurement to observe image-sticking phenomenon.

Table 2 Simulation results of grayscale voltage in IPS cells.

Gray Level	AC voltage
63 Gray	2.3 V
127 Gray	3.0 V
191 Gray	3.6 V
255 Gray (White)	5.1 V
VT peak voltage	5.5 V

2.3 Simulation Method of Electric Field

To confirm the relationship between the short-term image-sticking phenomenon and the flexoelectric effect, we simulated an electric field in an LC layer in IPS cells with the simulation software LCD-Master 2D by Shintech, Inc.

The flexoelectric effect was added to LCD-Master 2D in the next formula, and we used the flexoelectric effect of e_s and e_b as +10 pC/m, respectively. Although we had no basis for the flexoelectric coefficients of LC, we believe the values of the flexoelectric coefficients set are reasonable, because larger flexoelectric coefficients make the VT peak voltage in the simulation lower and the discordance between simulation and real values in the VT peak voltage increases.

$$\boldsymbol{P}_f = e_s \cdot \boldsymbol{n}(\nabla \cdot \boldsymbol{n}) + e_b \cdot \boldsymbol{n} \times (\nabla \times \boldsymbol{n})$$

$\boldsymbol{P}_f$: Flexoelectric polarization

e_s and e_b : Splay and bend flexoelectric LC coefficients

Vector description of the LC director

First, we simulated a VT curve to calculate each grayscale voltage shown in Table 2. Grayscale was calculated to have a gamma value of 2.2 — the same as the IPS cell measurement.

The differences between the measurements and the simulation results were presumably influenced by measurement errors in the LC parameters taken during the simulation. It is well known that measurement errors of the (twist elastic constant) K22 are large and the VT curve of the IPS mode is affected by the K22.

An electric field simulation was carried out using the dynamic mode of LCD-Master 2D. We set one period of a driving frame at 16.6 ms. Each positive and negative frame of the electric fields was simulated every 0.2 seconds, (giving 166 results total). We then averaged all of the electric field simulation results.

3. Result and Discussion

The measured transmittance change at 63 Gray (AC 2.8 V) is shown in Fig. 5. During the 63 Gray level applied from 0

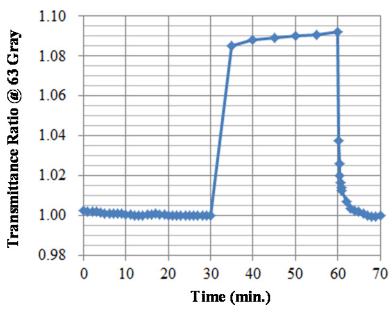


Fig. 5 Transmittance change at 63 Gray level applying 255 Gray level AC stress.

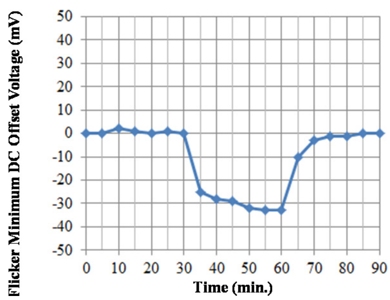


Fig. 6 Residual DC voltage measurement results driving 255 Gray AC stress.

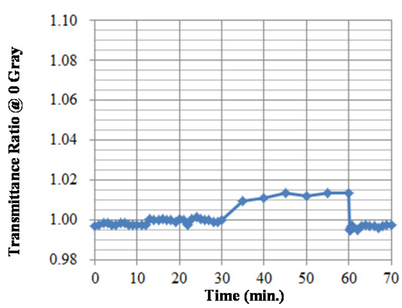


Fig. 7 Transmittance change at 0 Gray level applying 255 Gray level AC stress.

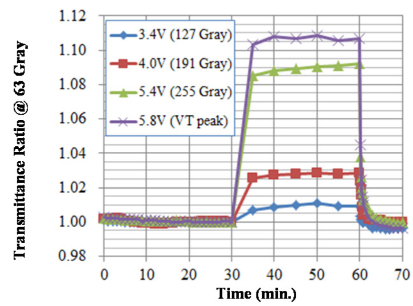


Fig. 8 Transmittance change at 63 Gray level applying various types of AC stress.

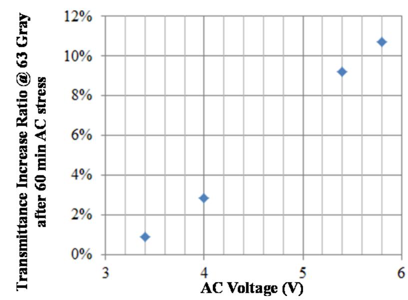


Fig. 9 Transmittance increase ratio dependence on AC voltage.

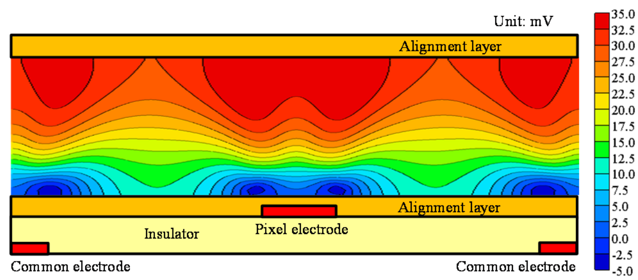


Fig. 10 Simulation result of time-averaged electric field in IPS cell with flexoelectric effect.

to 30 min, transmittance did not change. However, transmittance at 63 Gray rose by about 9%, while stress AC voltage (255 Gray, AC 5.4 V) was applied from 30 to 60 min. While 63 Gray level was applied again from 60 to 70 min, transmittance at 63 Gray decreased to its original value. Thus, we confirmed the short-term image-sticking phenomenon by applying 63 Gray AC voltage after 255 Gray AC stress.

Next, we measured RDC voltage when 255 Gray voltage was applied, because if a large RDC voltage occurred due to material properties or the asymmetric structure between pixel and common electrodes, there is a possibility that transmittance at 63 Gray will increase due to the RDC. The generation or recovery behavior of RDC voltage is shown in Fig. 6. We confirmed RDC generation with a value of −30 mV, but a transmittance change caused by RDC of −30 mV was under 1%, as shown in Fig. 2. It is clear that the transmittance change in Fig. 5 cannot be explained by RDC.

The measured transmittance change at 0 Gray (AC 0.01 V) is shown in Fig. 7. The transmittance at 0 Gray increased after applying 255 Gray stress, as seen in Fig. 5, but the ratio of increase was only about 1%. If the increase in transmittance in Fig. 5 was light leakage caused by a disorder of the LC director due to 255 Gray AC stress application, the transmittance in Fig. 7 would become much bigger than 1%, because that at 63 Gray is much brighter than that at 0 Gray. Thus, it is clear that the increase in transmittance was not caused by light leakage due to applying 255 Gray AC stress.

The measured transmittance at 63 Gray with various types of applied AC stress voltage is shown in Fig. 8. Furthermore, the transmittance increase ratio over 60 min is shown in Fig. 9. The transmittance increase ratio was generated from a nearby AC stress of 3.0 V and changed almost linearly depending on AC stress voltage from 3.0 V to VT peak voltage.

The simulation results of a time-averaged electric field are shown in Fig. 10. An averaged electric field caused by the flexoelectric effect indicated vertical distribution. We

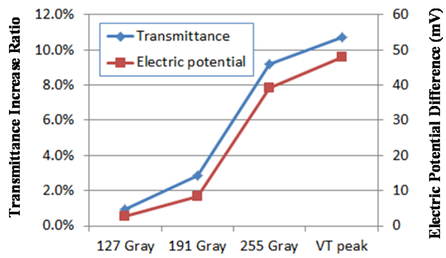


Fig. 11 Transmittance increase ratio and electric potential difference caused by various AC voltages.

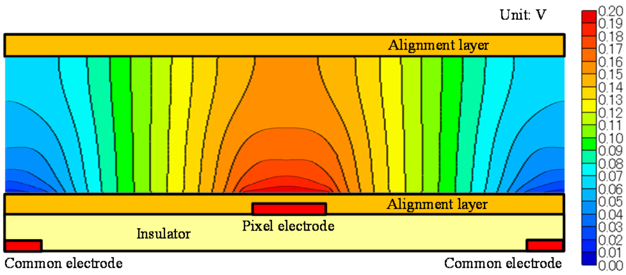


Fig. 12 Simulation result of time-averaged electric field at DC +200 mV without flexoelectric effect.

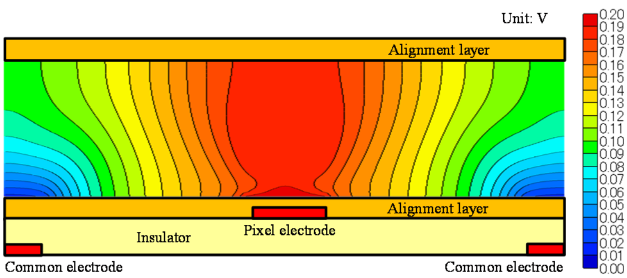


Fig. 13 Simulation result of time-averaged electric field at DC +200 mV with flexoelectric effect.

believe the electric field distribution originates from bend flexoelectric polarization which originally appears in the vertical direction, and vertical components of splay flexoelectric polarization.

The ratio of increase in 63 Gray transmittance and the electric field distribution from applying various AC stress voltages are shown in Fig. 11. As the measurement results of the 63 Gray transmittance increase ratio were similar to the simulation results of the time-averaged electric fields, vertical electric fields caused by the flexoelectric effect affected this short-term image-sticking phenomenon. A vertical electric field induced an ionic relaxation; LC director change occurred and 63 Gray transmittance increased because the ionic relaxation did not disappear quickly after AC stress voltage application has been stopped.

Averaged electric field simulation results with DC +200 mV are shown in Figs. 12 and 13. When the flexoelectric effect did not occur, only a DC electric field of +200 mV appeared between the pixel and common electrodes. On the other hand, when the flexoelectric effect occurred, a vertical electric field appeared in addition to the DC electric field of

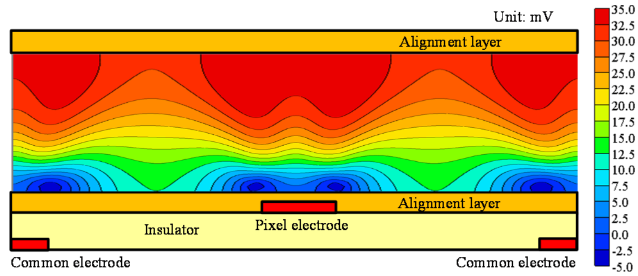


Fig. 14 The differences between Fig. 12 (DC +200 mV without flexoelectric effect) and Fig. 13 (DC +200 mV with flexoelectric effect).

+200 mV between the pixel and common electrodes.

The differences between Figs. 12 and 13 are shown in Fig. 14. Figure 14 is similar to Fig. 10 because the electric field caused by the flexoelectric effect was completely isolated from the DC bias voltage, from the common to pixel electrodes. In other words, residual DC voltage was not caused by the flexoelectric effect.

There are many kinds of polarization: electric polarization, ion polarization, orientation polarization, and ionic relaxation. The kind that plays the most important role in the driving liquid crystal layers is orientation polarization.

Though LC molecules have a permanent dipole moment, when an electric field is not applied, polarization does not occur because the director ratio of right and left is equal in the nematic phase. However, when an electric field is applied, polarization is generated in liquid crystal layer because the director ratio of right and left becomes unequal. Thus, when an electric field is applied, polarization is generated by orientation polarization in the nematic phase.

On the other hand, when wedge-type molecules are injected into wedge-type cells, for example, polarization is generated because excluded volume effects cause the director ratio of right and left to become unequal. This is the mechanism of polarization generation due to the flexoelectric effect (flexoelectric polarization). Furthermore, when the electric field is applied, flexoelectric polarizations of splay deformations and bend deformations are generated in IPS mode; this is called the "converse flexoelectric effect" [5].

As both the flexoelectric effect and the orientation polarization are generated by the converse flexoelectric effect, it is considered that the flexoelectric effect slightly changes the conditions of orientation polarization so that the dielectric constant anisotropy of the liquid crystal mixture becomes bigger or smaller for each local region. As a result, the flexoelectric effect does not generate large DC bias voltage between pixel and common electrodes, and it generates a weak vertical electric field in IPS mode.

4. Conclusion

When a white image is displayed on an IPS-mode LCD, a vertical electric field forms over time due to the flexoelectric effect in the splay deformation and in the bend deformation regions. A vertical ionic relaxation is generated because the electric field changes the ion distribution in liquid crystal layers. For example, if we apply a gray level after applying a white level, image sticking will occur because ionic relaxation causes the LC director in the gray level to be changed by the electric field.

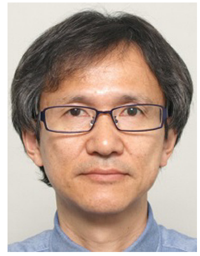
As electric fields caused by a flexoelectric effect do not correspond to those caused by DC bias voltage between pixel and common electrodes, RDC is not generated by the flexoelectric effect.

References

[1] Y. Momoi, K. Tamai, K. Furuta, T.-R. Lee, K.-J. Kim, C.-H. Oh, and T. Koda, "Mechanism of image sticking after long-term AC field driving of IPS mode," Journal of the Society for Information Display, vol.18, no.2, pp.134–140, 2010.
[2] Y. Shin, M. Jung, B. Jeon, K. Shin, and N. Roh, "An analysis method of image sticking of LCD," SID Symposium Digest of Technical Papers, vol.47, no.1, pp.1693–1696, 2016.
[3] R.B. Meyer, "Piezoelectric effect in liquid crystals," Phys. Rev. Lett., vol.22, no.18, pp.918–921, 1969.
[4] M. Inoue, N. Manabe, and J. Nakanowatari, "Correlation between flicker minimizing method and dielectric absorption method for residual DC voltage measurement," AM-LCD 97 Digest, pp.151–154, 1997.
[5] M. Ozaki and K. Yoshino, "Flexoelectric effect," Ekisho, vol.6, no.1, pp.22–33, 2002.
[6] D. Inoue, T. Miyake, and M. Sugimoto, "A mechanism of short-term image-sticking phenomenon caused by flexoelectric effect in IPS LCD," Proc. International Display Workshops, vol.24, pp.288–291, 2017 (in Japanese).

Daisuke Inoue received his B.S. and M.S. degrees in polymer chemistry from Tokyo Institute of Technology in 1994 and 1996, respectively. He joined NEC Corporation, where he was engaged in developing materials for TN and IPS LCD panels. During 2009–2015, he was with the LCD division at Samsung Electronics or Samsung Display, where he researched and developed LCD panels. He is now a member of the panel development department of Tianma Japan, Ltd.

Tomomi Miyake received her Bachelor of Biomedical Engineering degree from Kagoshima University in 2005. She joined NEC Corporation, where she engaged in developing materials for LCD panels. In 2011, she joined NLT Technologies, Ltd. (now Tianma Japan, Ltd.).



Mitsuhiro Sugimoto received B.S. and M.S. degrees in applied physics engineering from Waseda University in 1985 and 1987, respectively. He joined NEC Corporation, where was engaged in the development of electronic component devices such as automotive sensors and piezoelectric transformers. Since 2011, he has been involved in basic technology development of LCDs at NLT Technologies, Ltd. (now Tianma Japan, Ltd.).