FFS-mode OS-LCD for reducing eye strain

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Abstract — In order to reduce eye strain, a driving method for reducing flickers of liquid crystal display (LCD) is devised. For this driving, an oxide semiconductor (OS) is used in a backplane, liquid crystal and alignment layer materials are optimized, and a fringe field switching (FFS) mode with a structurally formed storage capacitor is used. This work reveals that suitable usages of positive and negative liquid crystals differ from each other according to their characteristics. This work also describes an OS-LCD with a touch sensor we fabricated for mobile devices, which proves the possibility of reducing-eye-strain technology (REST) with reduced flickers.

Keywords — liquid crystal display, dielectric anisotropy, transmittance change, crystalline oxide semiconductor, eye strain.

DOI # 10.1002/jsid.196

1 Introduction

With the recent development of the information society, display screens are more often viewed for longer periods of time. This has increasingly imposed eye strain. A significant countermeasure against the burdens on eyes is devising displays. Increasing definition, reducing flickers, cutting off blue light, slow changing of images, and so on are considered effective in a reduction of eye strain.1–4 Our proposed solution is an OS-LCD with field-effect transistors (FETs) employing In–Ga–Zn oxide (IGZO), which has a c-axis aligned crystal (CAAC) structure.

A feature of an OS is its higher mobility than that of amorphous Si (a-Si). As for the OS, Kimizuka et al. synthesized IGZO for the first time in the world, and made clear its crystal structure.5–8 Then we discovered the CAAC structure in crystalline IGZO. As a result, FETs having low leakage current, a small size, and high reliability have been obtained.9–12 Extremely low leakage current, which is a feature of OS, enables a signal to be held for a longer period. In a normal liquid crystal panel, data are written 60 times per second, that is, at a rate of 60 Hz, but when images do not need to be changed such as a still image, data are not written as long time as possible. Consequently, frame frequency and power consumption can be reduced.

Attempts at such low-frequency driving, that is, idling stop (IDS) driving, and low power consumption by employing OS were previously reported.13–19 This driving should be eye-friendly reducing-eye-strain technology (REST) driving with reduced flickers. The IDS driving also opens the possibility of reducing eye strain in conjunction with downsizing a pixel and achieving higher-definition display. Higher definition and lower power consumption are also strongly demanded for mobile devices. An OS-LCD panel using CAAC-OS is hence suitable as the countermeasure for a reduction in eye strain. Note that the IDS driving, which is essentially intended for still images, can be switched to normal 60-Hz driving for moving-image display.

In an active matrix method, a voltage applied to each pixel normally needs to be held without any decay until the next writing operation. This is more sorely needed in the IDS driving with low frame frequency. The voltage holding ratio (VHR) of a cell is by no means 100%, and a leakage current is generated. Further, such driving can be regarded as pseudo-DC driving and might involve localization of ionic impurities because of long-time application of a voltage of one polarity or cause a change in effective voltage. These entail a transmittance change, which might result in flickers or burn-in on the display. Suppression of a transmittance change is thus a key factor for a reduction of eye strain.

A voltage change can be effectively suppressed by enlarging a storage capacitor, but this increases the pixel size, decreases the aperture ratio, and makes charging difficult. Therefore, this method alone is not favorable.

Received 7/31/13; accepted 11/22/13.
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442 Journal of the SID 21/10, 2014
In this work, we solve the problem of a transmittance change in the low-frequency driving by using CAAC-OS in FETs and by examining materials and liquid crystal mode, and describe a panel we fabricated for mobile devices employing REST, which causes less eye strain.

2 FET for REST

Leakage during voltage holding by the IDS driving is considered here. There are mainly two leakage paths: an FET and a liquid crystal or alignment layer material. An equivalent circuit of a pixel is shown in Fig. 1, in which the structure around a liquid crystal is simplified.

A comparison is made between common low-temperature poly-silicon (LTPS), a-Si, and CAAC-OS FETs. The current $I$ flowing out of the circuit can be estimated using the following formula:

$$ I = -C \frac{dV}{dt} $$

where $C$ is the capacitance of a capacitor, $V$ is voltage, and $t$ is time.

Table 1 shows the leakage current $I_{\text{off}}$ with a channel length $L = 3 \, \mu\text{m}$, the ratio of channel width $W$ to channel length, and the voltage change $AV$ with respect to holding time. To simplify calculation, the capacitance of the circuit is assumed to be 100 (fF).

The table shows that LTPS and a-Si FETs have no problem in normal 60-Hz driving but have significant voltage increases in long-time holding. In 5 V driving at 1 Hz, the voltage change would be as large as or larger than 1%. In this regard, the use of CAAC-OS with lower leakage current is effective in achieving IDS driving with less transmittance change.

A large storage capacitor can suppress a voltage change but decreases the aperture ratio. The use of CAAC-OS is also effective in obtaining a downsized FET with high mobility.

The $I_{\text{off}}$ of CAAC-OS is $<10^{-19} \text{ (A/\mu m)}$ [$>10^{23} \text{ (\Omega cm)}$], which is negligibly low compared to that of a liquid crystal or alignment layer material [$<10^{16} \text{ (\Omega cm)}$]. This means that only materials need to be taken into consideration of leakage current.

3 Material for REST

A problem with the conventional IDS driving is that a transmittance change is larger in halftone display than in black or white display. Figure 2 shows transmittance changes. These measurement results are attributed to a difference between slopes of the $V$–$T$ curves in the black or white display and in the halftone display. As the slope increases, the transmittance change also increases even when the amount of voltage change is the same. In view of halftone display, the voltage change needs to be further suppressed.

To suppress such a transmittance change and achieve eye-friendly driving, an examination is made below of liquid crystal materials and alignment layer materials suitable for the REST driving.

3.1 Liquid crystal material for REST

As ionic impurities induce leakage current or residual voltage, it is important to prevent entry of ionic impurities into a cell. Although there is no simple correlation between ionic impurities and dielectric anisotropy ($\Delta\varepsilon$) in a liquid crystal mixture, in the choice of a liquid crystal material, our focus is placed on $\Delta\varepsilon$ as one measure.

To estimate the influence of ionic impurities, $L$–$V$ characteristics and residual DC voltages were measured using a large storage capacitor.
The liquid crystal material characteristics measurement system Model 6254 produced by TOYO Corporation, Tokyo, Japan. The \( I-V \) characteristics were measured by observing current responses to 0.05-Hz triangle waves applied to samples. The residual DC voltages were obtained by measuring cell voltages generated by dielectric absorption after applying 6V to the samples for 1h, shorting the circuits for discharging, and then opening the circuits. Each measurement was conducted at a temperature of 30 °C. Table 2 shows physical properties of liquid crystals used for the measurements. Cells with a gap of 4 \( \mu \)m and without alignment layers were measured.

Figure 3 shows results of \( I-V \) measurements made on three liquid crystals having different \( \Delta \varepsilon \). The figure demonstrates that a liquid crystal having higher \( \Delta \varepsilon \) exhibits a higher peak of minute current. This peak indicates movement of ionic impurities, and a large peak value means a high density of ionic impurities.

Figure 4 shows measurement results of residual DC voltages. The figure demonstrates that a higher residual voltage is generated with increasing \( \Delta \varepsilon \). Thus, in terms of ionic impurities, a LC_A having lower \( \Delta \varepsilon \) is more effective in the eye-friendly driving.

Figure 5 shows voltage changes and VHRs at 30 °C of liquid crystals having different resistivities. The VHRs were obtained from the area ratio of a voltage held by the samples after opening the circuits after 5s. The measurement results suggest that VHR increases as a resistivity increases. High VHR is essential in suppressing a transmittance change during a signal holding period. This also indicates the superior effectiveness of the LC_A in the eye-friendly driving in terms of VHR, owing to its high resistivity.

### 3.2 Alignment layer material for REST

The choice of an alignment layer material is also important in consideration of residual voltage. The Maxwell–Wagner theory about multilayer dielectric gives the following equation:

\[
\varepsilon_{LC} \rho_{LC} = \varepsilon_{AL} \rho_{AL}
\]  \( \text{(2)} \)

where \( \varepsilon \) and \( \rho \) represent the dielectric constant and the resistivity, respectively, and \( LC \) and \( AL \) represent the liquid crystal and the alignment layer, respectively. When this equation is satisfied, electric charges do not accumulate at the interface between the liquid crystal and the alignment layer, thereby generating no residual voltage. In general, the resistivity of a liquid crystal is on the order of \( 10^{13} - 14 \) (\( \Omega \) cm) and that of an alignment layer is on the order of \( 10^{15} - 16 \) (\( \Omega \) cm). Thus, to make the resistivities as close to each other as possible is a strong countermeasure against residual voltage. To do this, there are roughly two possible approaches: increase the resistivity of a liquid crystal or decrease the resistivity of an alignment layer. Increasing the resistivity of a liquid crystal is more effective in terms of voltage holding, as described in the preceding section. Thus, decreasing the resistivity of an alignment layer is examined here. Table 3 shows physical

### TABLE 3 — Physical properties of liquid crystals.

<table>
<thead>
<tr>
<th></th>
<th>LC_A</th>
<th>LC_B</th>
<th>LC_C</th>
</tr>
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<tbody>
<tr>
<td>( \Delta \varepsilon )</td>
<td>3.8</td>
<td>5.3</td>
<td>9.9</td>
</tr>
<tr>
<td>( \rho ) (( \Omega ) cm)</td>
<td>( 4.9 \times 10^{14} )</td>
<td>( 8.1 \times 10^{13} )</td>
<td>( 2.9 \times 10^{13} )</td>
</tr>
</tbody>
</table>
properties of alignment layer materials used for measurement. Twisted nematic (TN) cells with a gap of 4 μm were measured.

Figure 6 shows measurement results of residual DC voltages in the case of using alignment layers having different resistivities. The results verify that residual voltage can be lowered with the use of an AL_B having lower resistivity. However, a decrease in resistivity causes an increase in leakage current and a decrease in VHR, as shown in Fig. 7.

Residual DC voltages and VHRs are known to change significantly depending on the combination of a liquid crystal material and an alignment layer material as well as their resistivities.22 However, the decrease in resistivity is not desirable for the IDS driving, which requires signal holding.

Consequently, for the IDS driving, it is desirable to use an AL_A having high resistivity and make the resistivities of a liquid crystal and the alignment layer close to each other by increasing the resistivity of the liquid crystal.

The foregoing results reveal that the countermeasure for the eye-friendly driving from the aspect of materials consists of the following three points: suppression of the influence of ionic impurities by use of a liquid crystal having low Δε; an increase in VHR by use of a material having high resistivity, and a reduction in residual voltage by making the resistivities of an alignment layer and a liquid crystal close to each other by increasing the resistivity of the liquid crystal. Among the materials used in this work, the LC_A and the AL_A are a favorable combination.

| Table 3 — Physical properties of materials. |
|-----------------|-----------------|-----------------|
| p (Ω cm)        | AL_A            | AL_B            | LC_A            |
|                 | 4 × 10¹⁵        | 2 × 10¹⁴        | 4.9 × 10¹⁴      |

4 Liquid crystal mode for REST

High VHR is needed to hold a signal even with fewer writing operations. Enlargement of a storage capacitor can increase VHR but increases pixel size and lowers aperture ratio. This is unfavorable to a reduction of eye strain and to use in mobile devices. An attempt to solve this problem is made here by the choice not only of materials but also of liquid crystal mode.

4.1 Comparison of VHR

In the in-plane switching mode using a horizontal electric field, VHR is higher than in a TN mode in which a vertical electric field is applied to liquid crystal, as already known.23 This is because a capacitor of a glass substrate can be considered to be electrically connected in parallel to liquid crystal. The FFS mode using a fringe electric field is expected to exert the same effect. Figure 8 illustrates equivalent circuit models.

In the fringe electric field, an insulator between electrodes serves as a capacitor and can be considered to be electrically connected in parallel to liquid crystal. This is probably the cause of higher VHR of the whole cell.
Figure 9 shows measurement results of the voltage changes and VHRs of the LC_A with vertical electric field and fringe electric field. Cells with a gap of 4 μm were measured. The electrodes are patterned into actual panel pixel electrode structures.

Figure 9 demonstrates that the VHR in the fringe electric field is higher than that in the vertical electric field. This verifies that the capacitor formed by the insulator between the electrodes increases VHR. Further, because of this capacitor, no additional external storage capacitor, which might reduce transmittance, is necessary. Hence, a pixel can be downsized and an aperture ratio can be increased, thereby increasing definition and transmittance and reducing eye strain.

The FFS mode is thus suitable as a countermeasure against flickers in terms of VHR.

4.2 Comparison of V–T characteristics

The transmittances in the TN mode and the FFS mode were estimated by simulation. Results are shown in Fig. 10. The LC_A was used as a liquid crystal, and LCD Master made by Shintech Inc., Yamaguchi, Japan, was used for calculation. Cell gaps are each adjusted such that the transmittance can be maximized. The aperture ratio in an actual panel is not considered. The transmittances are normalized for easier comparison.

Figure 10 shows that, in the FFS mode, the slope is gentler, and a deviation in gray level with varying voltage can be more suppressed. Although the high saturation voltage increases the driving voltage, the FFS mode promises a backlight having lower power consumption owing to the higher aperture ratio.

Considering incorporation of a touch sensor for use in mobile devices, a horizontal electric field, which is resistant to pushing force, is advantageous. The FFS mode is hence used in the panel for mobile devices in this work.

5 Positive and negative liquid crystals

5.1 Flexoelectric effect

In the FFS mode, a horizontal electric field is mainly used. However, at the edge of electrodes, for example, a strong electric field is generated in an oblique direction, causing deformation such as splay deformation. It is therefore known that a flexoelectric effect occurs in the FFS mode. The flexoelectric effect refers to a phenomenon in which a nematic liquid crystal exhibits spontaneous polarization under splay or bend deformation.\(^{24}\)

To liquid crystal molecules themselves, the polarity of an applied voltage does not essentially make a difference, but spontaneous polarization tends to exhibit opposite behaviors based on the polarities of an electric field. This probably produces a difference between the polarities, and a transmittance change depending on the polarity affects display.\(^{25,26}\)

Flexoelectric polarization \(\vec{P}\) caused by the flexoelectric effect can be written in the following formula:

\[
\vec{P} = e_{\text{play}} (\vec{n} \cdot \vec{n}) + e_{\text{bend}} (\vec{n} \times \nabla \times \vec{n})
\]  

(3)

where \(e\) represents the flexoelectric coefficient mainly based on molecular shape and \(n\) represents the liquid crystal director. The polarization is expressed as a product of the flexoelectric coefficient and the deformation. The flexoelectric coefficient is difficult to measure, and although some techniques have been reported, no standard method has been established yet.\(^{27}\)

This means that the occurrence of polarization can be suppressed, and flickers can be reduced by decreasing the flexoelectric coefficient or the deformation.

5.2 Positive and negative liquid crystals

Now, positive and negative liquid crystals are considered. In the FFS mode, in view of its driving principle, both positive and negative liquid crystals can be used. Table 4 shows physical properties of materials used, and Fig. 11 shows V–T characteristics.

The positive liquid crystal exhibits a difference in V–T characteristics between the polarities, which is probably
attributable to the flexoelectric effect, whereas the negative liquid crystal exhibits almost no such difference. The negative liquid crystal has a higher transmittance.

The negative liquid crystal tends to be perpendicular to an electric field, so it does not rise to any component other than a horizontal electric field and is not easily deformed. As the polarization is expressed as a product of the flexoelectric coefficient and the deformation, it appears that the negative liquid crystal exhibits less flexoelectric polarization and a smaller change in transmittance depending on the polarity, than the positive liquid crystal.

Although the negative liquid crystal generally has a large rotational viscosity coefficient and thus does not have very good response characteristics, the IDS driving does not require extremely high-speed response. A problem of the negative liquid crystal is its lower resistivity than that of the positive liquid crystal. The resistivity is an important factor in the IDS driving, as discussed earlier.

Next, the positive material is considered. The positive material exhibits a larger transmittance difference between the polarities than the negative material. Thus, it is difficult to achieve the same transmittance at every gray level. Even a small difference imperceptible in normal 60-Hz driving results in a clear flicker in the IDS driving.

For suppressing the influence of this difference between the polarities, there is a possible approach that is completely different from that adopted for suppressing flexoelectric polarization. That is, the polarity is not inverted until the image is changed. When the display image is changed at the time of polarity inversion, a flicker due to the difference between the polarities is hardly perceived. This display method requires holding a signal for a long time to keep displaying an image and is thus suitable for the positive liquid crystal material having high resistivity.

In summary, the negative liquid crystal exhibits a small difference between the polarities but is not suitable for long-time holding. On the contrary, the positive liquid crystal exhibits a large difference between the polarities but is suitable for long-time holding.

These findings show that different display methods are suitable for the positive and negative liquid crystals in the IDS driving. Namely, IDS driving for several seconds or shorter is suitable for the negative liquid crystal, and a display method in which IDS driving is performed for about 1 min or longer and the display image is changed at the time of polarity inversion is suitable for the positive liquid crystal.

## 6 Display panel

### 6.1 Panel specifications

We have fabricated a 3.64-in. high-definition OS-LCD. The panel has a touch sensor using capacitive touch technology. A display portion employs the IDS driving and changes images only when it senses touch, thereby having lower power consumption. During the IDS driving in which writing is stopped, noise due to writing is not produced. This improves the accuracy of the sensor. In this way, the IDS driving and the touch sensor are a good match.

Specifications of the liquid crystal panel are summarized in Table 5.

FETs used as a driver element include crystalline IGZO having a CAAC structure. Pixels and driver circuits, which include crystalline IGZO FETs including CAAC-IGZO, are formed over one substrate.

Figure 12 shows TEM images of the CAAC structures of IGZO. In the CAAC structure, c-axis alignment can be observed.

Figure 13 shows a display example of the panel.

### 6.2 Transmittance change in panel

The panel was fabricated with the optimum combination of the liquid crystal and the alignment layer, which was examined with test cells. That is a combination of a LC_D that is a negative liquid crystal with the AL_A, or a combination of the LC_A that is a positive liquid crystal with the AL_A. Figure 14 shows changes in halftone transmittances (T50) of the negative and positive liquid crystals when the IDS driving is performed for 1, 5, or 60 s.

<table>
<thead>
<tr>
<th>TABLE 4 — Physical properties of materials.</th>
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<tr>
<td></td>
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<tr>
<td>Δε</td>
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<td>ρ (Ω·cm)</td>
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| FIGURE 11 — V-T characteristics of positive and negative liquid crystals. |

<table>
<thead>
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<th>TABLE 5 — Specifications of the LCD.</th>
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<tr>
<td>Display type</td>
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<td>Screen diagonal</td>
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<tr>
<td>Resolution</td>
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<td>Pixel pitch</td>
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<tr>
<td>Pixel density</td>
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<tr>
<td>Liquid crystal mode</td>
</tr>
<tr>
<td>Aperture ratio</td>
</tr>
<tr>
<td>FET</td>
</tr>
<tr>
<td>Data driver</td>
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<td>Scan driver</td>
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The LC_A and LC_D both show a transmittance change of about 1% in the IDS driving for 1 s, and this corresponds to 2- or 3-gray levels and is imperceptible.

The negative LC_D shows a change of about 2% in the IDS driving for 5 s. At around this level or above, a flicker becomes perceptible depending on the display image. This confirms that IDS driving for less than about 5 s is suitable for the negative LC_D.

The positive LC_A is capable, owing to its high resistivity, of holding a signal even in the IDS driving for 1 min, at approximately the same level as the LC_D in the 5-s driving. Note that the LC_A has high gray-level dependence because of the difference between the polarities, and thus, the image needs to be changed at the time of polarity inversion. In terms of the transmittance change alone, the LC_A has proven to be capable of holding a signal for 3 min or longer. However, at present, if the holding period exceeds 2 min, burn-in might adversely affect display.

7 Conclusion

In order to suppress the generation of flickers for the purpose of reducing eye strain, CAAC-OS was used in FETs, and materials and a liquid crystal mode were optimized in this work. Low dielectric anisotropy, high resistivity, and making the resistivity of a liquid crystal close to that of an alignment layer are of significance from the aspect of materials. An effective liquid crystal mode is the FFS mode with a structurally formed storage capacitor.

Different display methods should be employed for negative and positive liquid crystals. IDS driving for several seconds or shorter is suitable for the negative liquid crystal, and a display method in which IDS driving is performed for about 1 min or longer, and the display image is changed at the time of polarity inversion is suitable for the positive liquid crystal.

The actual panel we fabricated has proved the possibility of driving with reduced flickers.

Acknowledgment

We would like to acknowledge Dr. Tadashi Akahane for his guidance and valuable discussions.

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FIGURE 12 — TEM image of IGZO. (a) Cross-section and (b) plan view.

FIGURE 13 — Display image.

FIGURE 14 — Transmittance changes depending on the type of a liquid crystal. (a) Negative liquid crystal and (b) positive liquid crystal.


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