

Refined Ultra-Low-Power FFS LCD with Enhanced Transmittance and Low Voltage Driving

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ABSTRACT

We have developed an ultra-low power FFS LCD with enhanced transmittance, low-voltage driving, and compatibility with low-refresh-rate driving. Utilizing zero-anchoring technology, excellent display performance, uniformity, and a wide operating temperature range were verified. In addition, improved reliability and favorable flicker performance also demonstrated the potential for integration with low-refresh-rate driving.

1 Introduction

For years, liquid crystal displays (LCDs) have been widely adopted in mobile devices such as tablet PCs and laptops. The Fringe Field Switching (FFS) mode is a particularly suitable LCD mode as it not only offers superior image quality but also compatibility with in-cell touch technology. While the development of OLEDs, microLEDs, nanoLEDs, and other emissive display technologies continues to advance, LCDs remain a viable option due to their low power consumption and cost-effectiveness. Notably, amidst the current market trend emphasizing sustainability and environmental friendliness, energy savings have become a crucial focus.

In 2022, we proposed a low-power LCD featuring a Zero Anchoring (ZA) interface [1]. Following this, we advanced the development of materials and panel design with a focus on mass production, resulting in the fabrication of high-quality panels that exhibit high quality, improved reliability, and manufacturability. Additionally, in recent years, low-frequency driving technologies have also been actively developed to reduce the power consumption of LCDs [2,3]. In this paper, we also discuss the integration of the LCD with the ZA interface and low-frequency driving, demonstrating its feasibility [4].

2 Panel configuration

The fundamental structure of the panel is similar to that reported in 2022. Specifically, as shown in Figure 1, 1) the CF substrate is coated with a zero-anchoring alignment material while the TFT side is coated with a strong anchoring material; 2) the thickness of the liquid crystal (LC) layer is smaller than the recommended values for conventional LCDs; and 3) the LC material exhibits positive dielectric anisotropy. Figure 2 shows the typical voltage-transmittance (VT) characteristics, indicating that

the ZA-FFS operates with a higher transmittance than the FFS with negative dielectric anisotropic LC (n-FFS) and operates with a lower driving voltage than the FFS with positive dielectric anisotropic LC (p-FFS). LC molecular motion is lubricated by the ZA interface, realizing lower driving voltage and higher transmittance.

To advance towards mass production, we re-optimized the LC and alignment layer materials along with the panel design. Although one might assume that the use of a zero anchoring alignment layer would require a specialized coating or formation process, the panels in this study were fabricated utilizing the current process conditions without any additional investment or modifications to existing LCD manufacturing facilities. This is highly favorable from the perspectives of productivity and operational efficiency for LCD manufacturers that produce a variety of models depending on customers' requirements.

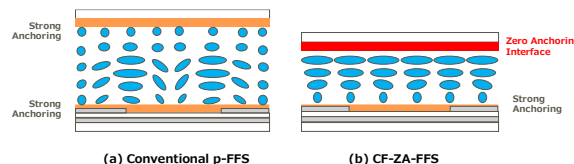


Fig. 1 Cross-sectional view of the LCDs

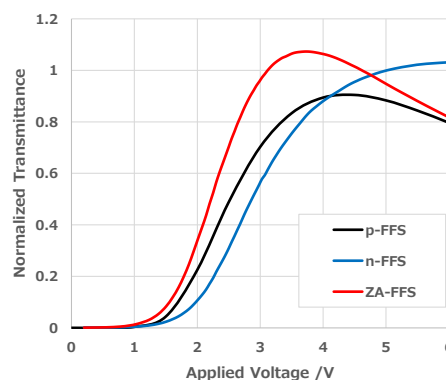


Fig. 2 VT characteristics

3 Display performances

3.1 Uniformity

In our previously reported panels, brightness non-

uniformity was observed when displaying gray levels (for example, V64). To address this issue, we have developed alignment materials and processes that improve alignment uniformity and have mass production capability. Figure 3(a) shows the previously reported panel, while Figure 3(b) shows the newly developed panel fabricated on the G4.5 line. Both panels display a gray image at V64. As can be seen, the new panel achieves a uniform display. We have confirmed that it remains uniform even when viewed from an angle and across different gray levels.

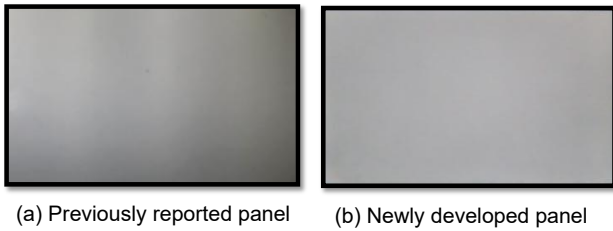
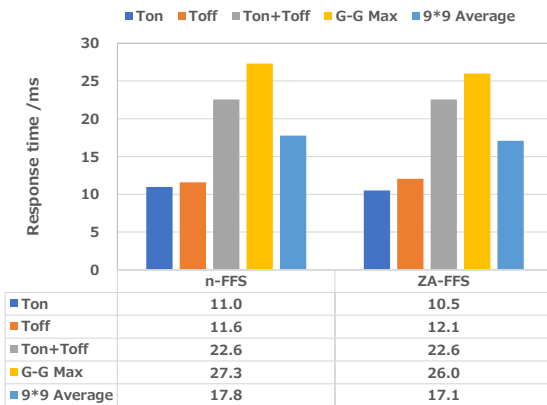


Fig. 3 Uniformity comparison at gray level V64

3.2 Response time

We evaluated the response time including the gray-to-gray (G-G) transitions across all 9x9 from and to combinations. The results are shown in Figure 4. The response time is defined as the time taken for the transmittance to change from 10% to 90%. The reference for comparison was the n-FFS panel with a negative dielectric anisotropic LC material, which is currently in mass production for laptop PCs. As shown in Figure 4, it was confirmed that not only the white-to-black response time (T_{on}) and black-to-white response (T_{off}) but also the G-G response was comparable to that of existing products. As mentioned in our previous report, the ZA-FFS has a disadvantage in terms of response time due to the weak restorative force of the LC molecules attempting to return to their original orientation. To address this issue, we improved the LC material by reducing its viscosity and increasing its elastic constant, and we also optimized the panel design intentionally decreasing the cell gap while maintain the transmittance.



(a) Response comparison

n-FFS		To								
		0	32	64	96	128	160	192	224	255
From	0		20.8 ms	26.0 ms	27.2 ms	26.2 ms	24.7 ms	22.2 ms	17.6 ms	11.0 ms
	32	8.5 ms		23.7 ms	27.3 ms	25.9 ms	24.4 ms	21.6 ms	17.3 ms	11.0 ms
	64	9.4 ms	16.9 ms		21.6 ms	24.9 ms	24.2 ms	21.5 ms	18.1 ms	10.6 ms
	96	10.1 ms	15.7 ms	18.4 ms		23.4 ms	23.4 ms	20.9 ms	17.4 ms	10.4 ms
	128	9.8 ms	14.3 ms	18.8 ms	22.3 ms		18.7 ms	18.8 ms	16.7 ms	10.1 ms
	160	10.3 ms	15.0 ms	18.2 ms	20.8 ms	17.1 ms		17.3 ms	15.5 ms	10.1 ms
	192	10.6 ms	14.1 ms	17.3 ms	21.0 ms	22.5 ms	18.0 ms		16.4 ms	9.6 ms
	224	10.7 ms	14.2 ms	17.7 ms	21.1 ms	21.6 ms	20.2 ms	18.3 ms		9.1 ms
	255	11.6 ms	14.5 ms	17.5 ms	20.7 ms	22.1 ms	21.0 ms	19.2 ms	15.0 ms	

(b) Response table for conventional n-FFS

ZA-FFS		To								
		0	32	64	96	128	160	192	224	255
From	0		20.1 ms	25.6 ms	26.0 ms	25.9 ms	23.8 ms	20.9 ms	18.0 ms	10.5 ms
	32	8.1 ms		23.7 ms	24.9 ms	23.9 ms	23.4 ms	20.2 ms	18.0 ms	10.2 ms
	64	10.1 ms	16.4 ms		22.8 ms	23.8 ms	22.1 ms	19.7 ms	17.6 ms	10.0 ms
	96	9.9 ms	15.5 ms	18.4 ms		22.5 ms	21.3 ms	19.0 ms	16.6 ms	9.5 ms
	128	10.0 ms	13.7 ms	17.5 ms	20.8 ms		18.8 ms	17.4 ms	16.3 ms	9.4 ms
	160	9.9 ms	13.6 ms	17.2 ms	19.9 ms	18.1 ms		17.2 ms	15.7 ms	9.1 ms
	192	10.3 ms	13.4 ms	16.8 ms	18.7 ms	18.2 ms	18.0 ms		15.5 ms	9.2 ms
	224	10.9 ms	14.0 ms	16.8 ms	18.8 ms	19.8 ms	19.2 ms	16.9 ms		9.4 ms
	255	12.1 ms	14.9 ms	18.2 ms	20.1 ms	20.3 ms	20.7 ms	19.2 ms	16.4 ms	

(c) Response table for the newly developed ZA-FFS

Fig. 4 Response characteristics

3.3 Image sticking

In the new prototype, we also evaluated the image sticking characteristics. A black-and-white checkerboard pattern was displayed to apply stress, followed by a full gray display at V128 for a specified duration. The brightness ratio of the areas that displayed white and black is defined as the burn-in rate ($T'/T - 1$). T' is the V128 brightness of the areas that displayed white during the burn-in test, while T is the V128 brightness of the areas that displayed black. The results are shown in Figure 5. Based on our past studies, it was established that a burn-in rate exceeding 1% becomes perceivable to the human eye, and we have set a target of keeping it below 1%. It was confirmed that the image sticking characteristics of the ZA-FFS are comparable to those of the currently mass-produced n-FFS panels.

Furthermore, similar to conventional FFS panels, the DC characteristics, exemplified by the Vcom drift, can be optimized based on the resistance of the alignment layer, specifically that of the alignment layer on the TFT side. In our panel design, the TFT substrate has a strong anchoring alignment layer, allowing for a more focused selection of an appropriate photo-alignment material from the existing lineup based on specific requirements.

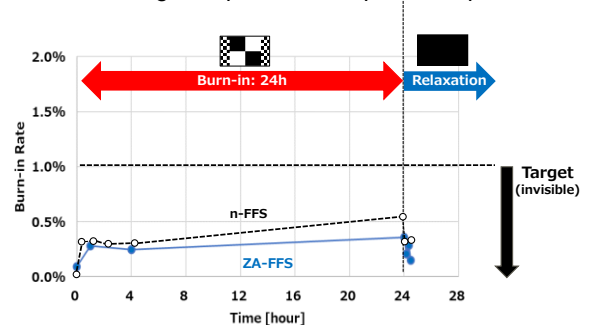


Fig. 5 Image sticking characteristics

3.4 Contrast ratio

The contrast ratio (CR) was also evaluated with the newly developed panel. Since the CR depends not only on the LC and alignment materials but also significantly on various other panel components such as a backlight, a polarizer, and a color filter, we conducted a thorough comparison of the native CR using a panel equipped with the same components, excluding the LC and alignment materials. The reference panel employs mass-produced photo-alignment and negative dielectric anisotropic LC materials. For the ZA-FFS configuration, we investigated two different types of LC materials, designated LC-1 and LC-2, which possess distinct physical properties. LC-2 is a newly developed material that has a larger elastic constant compared to LC-1 and effectively reduces light scattering originating from the LC layer. While material LC-1 exhibited poor CR performance, we confirmed that the new material LC-2 achieved a CR comparable to that of the current n-FFS. These results are based solely on the panel with a regular backlight, and an even higher CR of over 2000:1 can be expected, for example, by utilizing a collimated backlight, high CR polarizers and/or a low scattering, low retardation color filter.

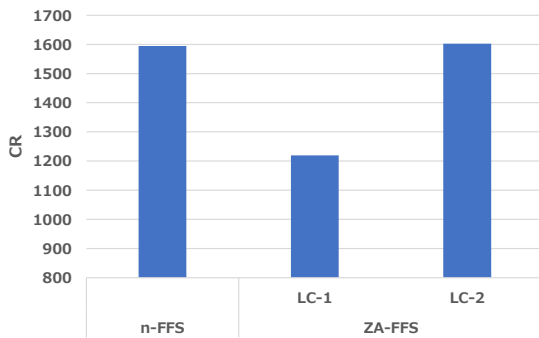
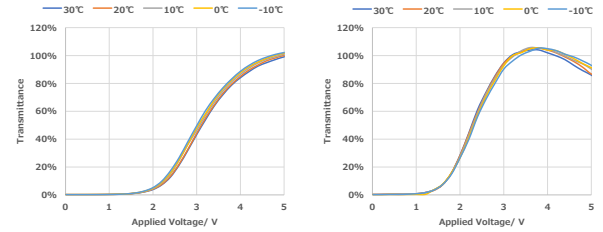


Fig. 6 Contrast ratio

3.5 Temperature dependence

Consumer LCDs for mobile PCs typically guarantee operation down to -10°C as part of their specifications. On the other hand, the zero-anchoring interface inherently exhibits a property in which anchoring becomes stronger as the temperature decreases. In fact, previously reported panels faced challenges related to temperature dependence, but as shown in Figure 7, we confirmed that optimizing the compatibility between the LC and the alignment materials enabled the newly developed panel to perform well down to -10°C . In addition, generally, LCDs can experience mura due to the temperature distribution from the backlight unit or mechanical factors, but our new prototype did not show any noticeable mura under such conditions.



(a) Conventional n-FFS (b) Newly developed ZA-FFS

Fig. 7 VT dependence on temperature

4 Towards the low-refresh-rate driving

In our efforts to further reduce power consumption, we have set an additional target we would like to achieve: compatibility with low-refresh-rate driving. Specifically, we focused on improving the voltage holding ratio (VHR) and reducing the flexoelectric effect. Controlling the VHR and flexoelectricity is crucial for mitigating flicker at low frequencies. From the perspective of the LC material composition, increasing the proportion of positive polar components tends to worsen the flexoelectricity, so the common strategy is to reduce the positive polar components. However, decreasing the positive components means a reduction of the dielectric anisotropy of the LC, resulting in an increased driving voltage. This would be counterproductive, as our goal is to achieve low power consumption while minimizing the driving voltage. In this context, LCDs with a zero-anchoring interface can be driven at low voltages even with low-dielectric LC materials, suggesting good compatibility between low-frequency driving and zero-anchoring.

To evaluate flicker during low-frequency driving and the VHR reliability, we fabricated test cells in our lab and conducted evaluations. Figure 8 shows the flicker evaluation results for the ZA-FFS compared with the n-FFS, measured using a display color analyzer (CA410, Konica Minolta). From the perspective of the flexoelectric effect, LCDs with positive dielectric anisotropic LC materials are generally affected by the flexoelectric effect, leading to brightness drops during polarity inversion (or spikes in brightness for high grayscale). However, the ZA-FFS exhibits minimized flexoelectric effects, demonstrating favorable flicker performance. Furthermore, at gray levels, the n-FFS exhibits a descending waveform during each frame, whereas the ZA-FFS shows an ascending waveform. This behavior can be explained by the time constants (resistances) of the panel materials, including the alignment material, in relation to the LC material. Specifically, the n-FFS uses negative dielectric anisotropic LC materials, which have a relatively low resistance, resulting in a descending waveform. In contrast, the ZA-FFS employs positive dielectric anisotropic LC materials, which have a

relatively high resistance, producing an ascending waveform. The reference n-FFS panel is currently marketed as a low-frequency driving (variable refresh-rate driving) LCD and shows no significant differences in performance or better performance.

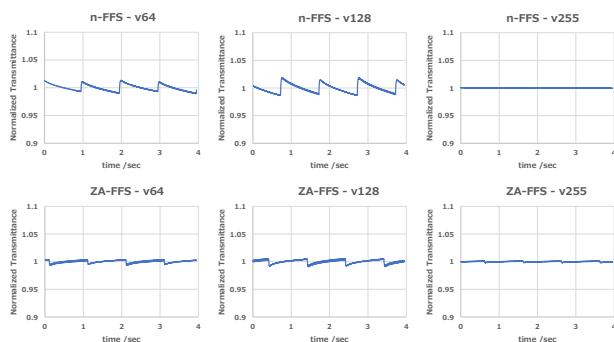


Fig. 8 Flicker characteristics of n-FFS and ZA-FFS at V64, V128, and V255

In the case of low-frequency driving, particularly at 1 Hz, the refresh period for one frame approaches 1000 ms, making the VHR characteristics of the LC crucial. This is because low VHR can cause voltage drops during one frame, resulting in reduced brightness, which is perceived as flicker. The risk of image persistence is also increased. In this study, we developed highly reliable LC materials and alignment materials in collaboration with material manufacturers. Figure 9 shows the VHR reliability results, measured using a LC material characteristics measurement system (Model 6254, Toyo Corporation). Similar to flicker, we confirmed that the performance of the ZA-FFS surpasses that of the n-FFS at 1 Hz. Our ZA-FFS utilizes positive LC material, which inherently offers greater potential for reliability compared with the n-FFS.

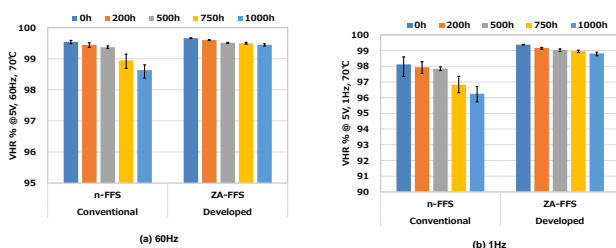


Fig. 9 VHR reliability

5 Prospects for middle-sized panels

Our primary target for applying this technology is mobile PCs and tablets with screen sizes ranging from 10 to 16 inches. As an example, we calculated the power reduction effect for a 15-inch QHD display in the white state with a brightness of 250 nits. The ZA-FFS results in a reduction in power consumption of approximately 20 mW when driving at 60Hz. Furthermore, operation at 1 Hz can lead to an additional reduction of 30 mW. These effects become more significant as the backlight brightness increases because the power consumption of the backlight is significant compared with that of the logic components. Additionally, low-frequency driving is applicable only when

displaying static images, but the ZA-FFS also enables low power consumption during high-frequency driving, which means the ZA-FFS can be effective in any use case.

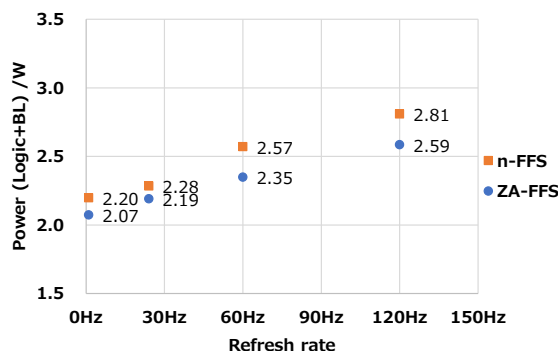


Fig. 10 Power consumption

6 Conclusions

We have developed the ZA-FFS, which features favorable transmittance, response time, image sticking characteristics, and operating temperature range. Improved reliability and its potential for 1 Hz operation were demonstrated through VHR and flicker evaluations, showing comparable or superior performance compared with existing n-FFS panels. The ZA-FFS technology we have reported contributes to energy savings in today's society, where sustainability is becoming increasingly important. Based on these results, we plan to prototype a middle-sized LCD with variable refresh-rate driving and oxide semiconductors on the G8 line in 2025.

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References

- [1] H. Asagi, K. Murata, K. Matsumoto, Y. Nishihara, Y. Hashimoto and K. Minoura, "An Ultra-Low Power FFS LCD Using Zero-Anchoring Interface", SID 2022 Digest, 337-340 (2022).
- [2] I. Miyake, H. Asagi, M. Shimizu, K. Matsumoto, Y. Nishihara, Y. Hashimoto, T. Matsushita, S. Shimada and Y. Ito, "Photo-alignment and n-FFS LCD Technologies with IGZO-TFT Applied to Generation Eight Factory", SID 2016 Digest, 592-595 (2016).
- [3] S-H. Baek, J-W. Jung, H-J. Park, D-J. Lee, S-M. Park, K-S. Kwon, H-S. Jin, H-B. Park, D-Y. Lee, M-S. Kim and S-H. Lee, "World's First 1 Hz Driving Fringe-Field Switching LCD for Power Saving", SID 2023 Digest, 803-806 (2023).
- [4] H. Asagi, D. Minami, K. Matsumoto, Y. Kawahira, A. Sakai and K. Minoura, "Ultra-Low Power FFS LCD with High Transmittance, Low-Voltage and Low-Refresh-Rate Driving", SID 2025 Digest, 290-293 (2025).