Advent, Evolution, and Recent Advances in FFS TFT-LCDs

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Keywords: Fringe-field switching (FFS), In-plane switching (IPS), Liquid crystals, TFT-LCDs

ABSTRACT

Since advent of fringe-field switching (FFS) mode which overcame demerits of the IPS mode while keeping its wide-viewing characteristics in 1998, it becomes a standard LC mode for small and medium-sized TFT-LCDs with high resolution, high image quality and low power consumption. The FFS LCDs still advance to large-sized LC-TVs with less color shift than OLEDs, and gaming monitors with superior performance in grey-to-grey scale response time of less than 4 ms and frame rate of 360 Hz in FHD, competing with multi-domain vertical alignment mode and emissive displays. In this talk, histories, evolution, and recent advances of FFS LCDs will be reviewed.

1. Advent of FFS TFT-LCDs

Since Hitachi co. reported very wide-viewing-angle LCD, so called in-plane switching (IPS) TFT-LCD in 1995 [1], and then Fujitsu co. reported multi-domain vertical alignment (MVA) TFT-LCD in 1997 [2], both became representative of wide-viewing-angle LC mode.

Although both IPS and MVA modes were mainly used by several companies for monitors at that time, we (engineers in HYDIS co.) believed both have intrinsic problems such as low transmittance and high operating voltages, which are not suitable for portable display application at all. Especially, when we made 12.1" IPS TFT-LCD by changing just few masks of TN LCD, we could realize the device shows an excellent viewing-angle but the transmittance was so low, which was not suitable to portable displays in our belief. Therefore, we had tested all kinds of electrode structure to find an optimal solution which can solve the problem of the IPS mode and then come to have the FFS idea and filed a patent in 1996 (see Fig.1 for comparison of electrode structure between IPS and FFS mode) [3]. Hereafter, the major milestone of the FFS TFT-LCDs is discussed.

<First stage>

The first feasibility of the FFS mode was tested using conventional 12.1" TN TFT-LCD by changing few masks. We divided one active area into four parts: 1) 1st ITO with plane shape (*l* = 0 μm), and 2-4) 1st ITO with slit shape (*l* = 1 μm). The first prototype was working fine while showing wide viewing-angle and much higher transmittance than that of the IPS-LCD (see Fig. 2). Once the feasibility of the FFS LCD was confirmed, 15.0" XGA TFT-LCD using a LC with negative dielectric anisotropy (-LC) was developed for monitor displays in 1998. The display showed the best transmittance compared with other wide-viewing-angle LCDs which we claimed this is the first device which shows wide-viewing-angle and high transmittance at the same time [3].

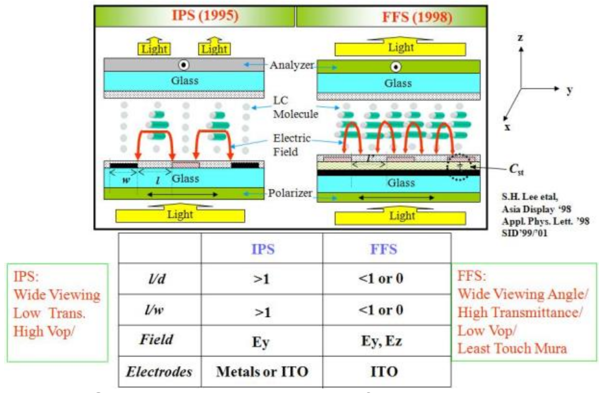


Fig. 1. Schematic comparison of electrode structures between IPS and FFS modes.

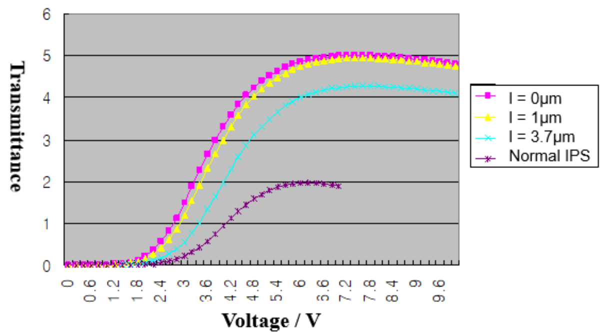


Fig. 2. Voltage-dependent transmittances depending on electrode structures in FFS and IPS modes.

Another unique and interesting feature of the display was found such that the display did not show ripple almost at all and pooling mura or pushed mark at all when an external pressure was applied to the panel device with fingers or pens. At that time, Wacom co. which makes pen-based 3D input displays for animation drawing works in Hollywood movies noticed strong merit of the FFS displays and commercialized the FFS display for the first time. Once the company used the FFS mode, they heard big compliment from their customers as follows "Tablets with conventional LCDs have Parallax issue and feel like drawing on a glass; however, with FFS Tablet PC, parallax issue is gone, and we feel like drawing on a paper". In fact, this pen-based display indicates the FFS LCD is suitable to touch screen display, which was already recognized in 1998.

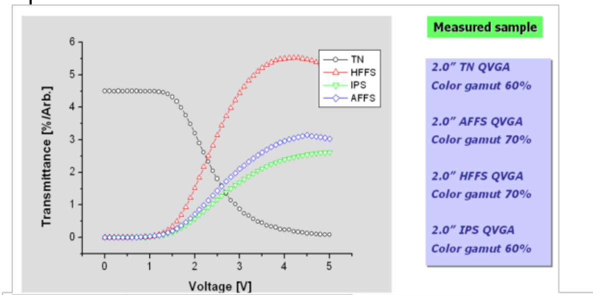
<Second stage>

Since mid-90s, the size of TFT-LCDs for monitor uses became bigger over 17" and the monitor played role of TV at the same time. The first FFS LCD used -LC of which the cost is rather high and its rotational viscosity is much larger than that of a LC with positive dielectric anisotropy (+LC) and its magnitude of dielectric anisotropy is much lower than that of +LC. Therefore, the FFS LCD with –LC shows rather slow response time and high operating voltage. Then we studied +LC, but if we just use a +LC with design concept of just IPS mode, the transmittance of the FFS LCD is not excellent anymore and some level of the pooling mura appears. We had optimized all panel and cell parameters (retardation, cell gap, initial LC orientation, electrode structures) to maximize performance of the FFS LCD with +LC and proposed "U-FFS" [4] which exhibits high transmittance, high contrast in wide range, minimized color shift, fast response, low power consumption.

The proposed concept becomes the basis of all FFS LCDs including tablet PCs, black and white displays for medical uses, monitor and LC-TVs in early 2000.

<Third stage>

In early 2000s, tablet LCDs with pen-based system with TN mode already existed. However, the TN mode shows very narrow viewing angle, which was not suitable to tablet PC because it can be displayed in either landscape or portrait type depending on users' will. In addition, the device must have high resolution like XGA in 12.1" so that maximizing transmittance while keeping wide viewing angle and low operating voltage was so important. As the pixel size becomes smaller, unwanted field direction around corners of pixel electrode was not negligible anymore and stability of LC's reorientation with +LC when an external pressure was applied was not satisfactory enough. Better pixel structure which solves this problem and improves transmittance in relatively high resolution FFS LCDs was proposed as A-FFS. In the middle of 2000s, Hydis and Seiko Epson tried to apply the FFS mode to super high resolution mobile LCDs. They proposed revolutionary pixel structure which maximizes transmittance in the FFS mode so called H-FFS [5]. The key structure of H-FFS is that the common electrode exists above pixel electrode and covers data line to shield off any noise field coming from the data line unlike that in conventional AFFS mode so that the transmittance near data line is maximized by removing LC disclination lines and minimizing width of black matrix (BM) on top substrates. As a result, the transmittance of HFFS LCD was improved more than 50% compared to conventional AFFS one and was even higher than TN LCD, indicating the FFS can exhibit higher transmittance than that of the TN when the display resolution reaches a certain high resolution, as indicated well in Fig. 3. Interestingly, a thicker inorganic insulator was used to minimize signal delay. This HFFS structure becomes the basis of present all high resolution FFS (IPS) LCDs from small to medium sized displays, though the inorganic layer is replaced by low dielectric organic insulator in a relatively large-sized displays. At that time, +LC was applied, so if we utilize –LC, the transmittance can be further improved more than 10%.



Items	2.03" AFFS	2.03" HFFS
Resolution	QVGA	QVGA
Color Gamut	NTSC 70%	NTSC 70%
Luminance	200 nit	312 nit
Contrast Raito	450 : 1	650 : 1
X-talk (H/V)	1.0% / 4.5 %	1.0%/1.0%
Transmittance (No gain)	4.0 %	6.2 %

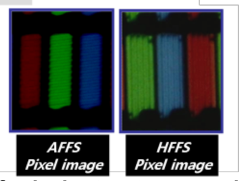


Fig. 3. Schematic comparison of pixel structures and measured V-T curves between AFFS, HFFS and TN TFT-LCDs [6].

2. Evolution of FFS TFT-LCDs

Since the first appearance of the IPS TFT-LCD in 1995, Hitachi kept improved its performance, reporting S-IPS and AS-IPS in '98 and '02. The AS-IPS used an organic resin to improve the transmittance which was not an easy process at that time and also it worsened image sticking problem. However, if they just adopt the FFS mode without using the resin, its transmittance and contrast ratio (CR) was higher than that of the AS-IPS with low operating voltage. Consequently, Hitachi reported new IPS so called IPS-Pro (FFS) in '04 [6], which surprises world's display industry and then the FFS mode becomes more noticed by other companies.

After first adoption of the FFS mode by Hitachi, the major company for small sized LCD, Seiko-Epson co., adopted the FFS mode for their super high resolution mobile LCDs in '06, which started application of HFFS to mobile LCDs.

Even after the above-mentioned historical movements the FFS mode was still not in main LC mode because the biggest LCD companies such as LGD, Samsung, Sharp, AUO etc did not use the mode although LGD used the FFS mode for their mobile LCDs. In 2010, a revolutionary product so called "iPhone4 Retina Display" and "iPad" was appeared by Apple Inc. At that time, the "retina display" had the highest 326 ppi resolution while keeping low power consumption and high image quality. On the other hand, the required concepts of the iPad product are as follows: 10 hrs uses without recharging the battery, wide-viewing-angle, touch display, sunlight readability. According to their analyses, the FFS LCD was the best to meet their requirements so that LCD panel maker LGD started its mass production with the FFS mode. Since then, the FFS LCD became the symbol of the high resolution and high performance TFT-LCDs. Since then, most of high-end displays even for notebooks and monitors adopted the FFS mode, replacing conventional film compensated WV-TN LCDs.

<Major Breakthroughs>

>Large-size and High Solution

Making high resolution FFS TFT-LCDs with high aperture for TVs was a challenging subject. Panasonic Co. reported the IPS-Pro-Next structure in 2012, in which a low dielectric organic insulator covers signal lines and a plane shaped common electrode covers all signal lines and TFT area, and then inorganic insulator and a patterned pixel electrode exist consecutively, as shown in Fig. 4 [7]. In this way, the BM width is minimized so that although the solution of the 47 ppi LCD increases to 109 or 216 ppi, an aperture ratio of 71% drops only to 66% at 216 ppi, indicating that IPS-Pro-Next is a very effective technology for realizing high transmittance and high-resolution LCDs. In 2018, Panasonic reported 55" 8K4K IPS LCDs with high frame frequency of 120 Hz and a-Si backplane, wide color gamut with laser light source, stereovision with polarization filter. The proposed pixel structure was applied to most of small and medium-sized high ppi FFS LCDs to realize high transmittance and low power consumption.

The FFS mode was known to be difficult to be applied to very large-sized TVs over 50" because the self-storage C_{st} was too big to charge in a large pixel size. Nevertheless, BOE Co. was so successful in commercializing FFS mode with further optimization in C_{st} and driving scheme, so called ADS mode, and reported 110" UHD 120Hz and QUHD, 98" QUHD, 82" 10K4K (Aspect ratio 21:9) and 65" QUHD in 2016 [8].

>Low Frequency Driving

Low frequency driving to reduce power consumption when displaying texts was troublesome in the FFS mode because strong splay and bend deformation in a white state forms net polarization P, which interacts differently between positive and negative frame field. This was suppressed by adopting a –LC with high resistivity and combination of oxide-TFT with negligible leakage current commercialized frequency tunable portable tablet PCs.

>Photoalignment Layer and -LC

Asymmetric light leakage in a dark state of the FFS LCD was generated due to existence of pretilt angle by rubbing process and more improvement on CR and better transmittance in high resolution displays were required. Then the photoaligned layer with zero pretilt

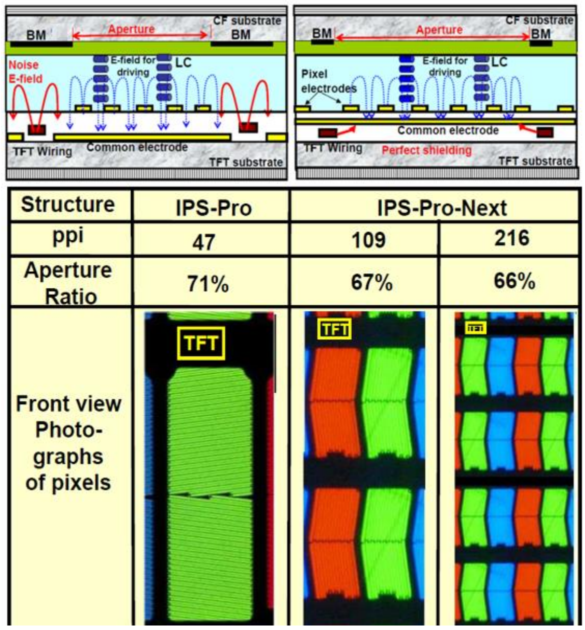


Fig. 4. Comparison of cross-sectional view of a pixel and photographs of pixels between IPS-Pro and IPS-Pro-Next [7].

angle and low viscosity of –LC were developed and commercialized.

3. Recent Advances, Challenges in FFS TFT-LCDs

> LC

At present, FFS LCDs use both +LC and –LC depending on application fields, that is, +LC for TVs, gaming monitors and automotive displays, and –LC for portable and low frequency driving displays. In order to improve low light efficiency of +LC, a LC with low magnitude of $\Delta\varepsilon$ and large magnitude of $\varepsilon_\perp$ is favored because the LC can rotate better above center of electrodes. However, use of low $\Delta\varepsilon$ LC will result in high operating voltage so that increasing $\varepsilon_\perp$ was approached by doping –LC to +LC while keeping a proper value of $\Delta\varepsilon$ [9]. For –LC, it becomes more popular as the display resolution becomes higher irrespective of display applications. Recently, BOE reported use of –LC in TV with rubbing process [10]. Consequently, LC makers focus on developing a single component or mixtures for low rotational viscosity of -LC.

> CR and High Dynamic Range (HDR)

Most of FFS/IPS LCDs have a CR less than 2000:1 while it is above 5000:1 in VA mode, that is, more fundamental studies are required to improve CR. In order to get fast response FFS LCD, a thin cell gap *d* must be used so that relatively high birefringent LC is favored to yield a high transmittance. Consequently, a –LC with low viscosity, high Δn, and high K is under developing to give rise to high CR and fast response time. In addition, when a thin *d* is used, even light efficiency of –LC drops so that fine patterning of electrodes close to 2 μm are favored to keep high transmittance and high CR [11].

Recently, LCD-TVs or tablet PCs wit HDR were commercialized to exhibit vivid images in which emissive displays are very difficult to realize peak brightness over 2000 nit. FFS LCDs with HDR and high CR over 1,000,000:1 was realized with use of either dual cell or local dimming mini-LED and an optical compensation film with reverse dispersion to remove a halo effect [12].

> Large-size TVs with high resolution, high frame rate

In this field, BOE Co. is leader, recently reporting a 65" 8K 120Hz ADS LCD TV based on oxide BCE with a high transmittance of 4.0% and a high charging rate of 92%. At the same time, BOE have developed the world's first 110" 8K ADS-LCD TV with 120Hz-driven [13].

> Low Frequency Driving

At present, 24 Hz driving FFS LCD is commercialized, while reducing flickering level is still under developing. Basic research on realizing lower or 1 Hz driving are under studying, in which both materials and design parameters need to be optimized.

> Gaming

Recently, gaming displays with higher frame rates with tunable frequency and higher resolution, i.e., FHD 360 Hz, QHD 240 Hz are favored and FFS LCDs with self C_{st} can meet those requirements better than VA mode with GTG response time less than 4ms. BOE reported 27" FHD 240 Hz refresh rate gaming product with GTG response time of 1.9 ms and CR of 1214:1 [14] and AUO reported 32" 8K4K 120 Hz FFS LCD with LTPS [15].

> Switchable Viewing-angle

Viewing-angle switchable functional FFS LCDs from wide to narrow view are under developing in which a vertical electric field is utilized to reorient LC director perpendicular to a substrate and then the light leakage at off-normal axis is generated in a narrow view mode. The light leakage either decreases CR or can be utilized to display some patterns which disturb the displayed images at off-normal axis [16]. Although blocking brightness at off-normal axis like Louver film is widely used, new approaches which can switch viewing angle without losing an optical efficiency are under developing.

> AR/VR

For high resolution and fast response time, Sharp Co. proposed diamond slit structure in 2.89" LCD with 706 ppi, in which the reorientation of LC switching occurs only by dielectric toque and fixed LC domain boundary exists, which enhances its response time to half of the conventional FFS LCDs [17].

> Polyimide (PI)-less Homogeneous Alignment

A conventional PI-less homogeneous alignment was proposed, which is eco-friendly process with less use of water and power and advantageous to fabricate flexible FFS LCDs [18]. All reported results require the process temperature higher than T_{ni}, which is not favorable. Room temperature process and materials need to be developed.

4. Summary

TFT-LCDs, especially with FFS LCDs become major displays in all application fields over two decades replacing emissive CRTs and PDPs owing to its revolutionary milestones in image quality, tunable driving frequency, cost, and form factor. More functional FFS LCDs such as viewing angle switching and 3D are coming. Flexible either FFS or any mode LCDs with free form factor need to be developed to extent its application fields. Although OLEDs penetrate markets not only mobiles and TVs but even IT and automotive displays nowadays and more emissive displays like QD-OLEDs and Micro-LEDs are coming, we believe TFT-LCDs will not fade away like PDPs and especially FFS LCDs with mini-LED and help of many revolutionary TFTs, optical components and materials can achieve a competitive or better image quality with less color shift and lower power consumption than emissive displays.

Display war has already started but we believe voltage-driven TFT-LCDs have strongest reliability with high performance and low cost, and its value can further be improved, and they may last in display markets enough long time like its intrinsic durability.

5. Acknowledgement

This work was supported by Regional Leading Research Center Program (2019R1A5A8080326) via the National Research Foundation (NRF) funded by the Ministry of Science and ICT of Republic of Korea.

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