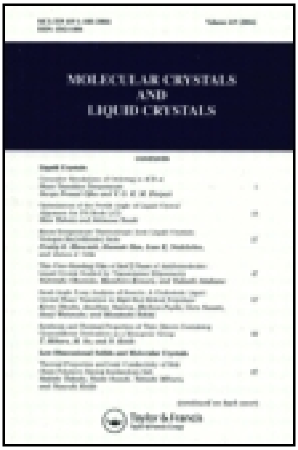

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Vertically Aligned TFT-LCDs

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VERTICALLY ALIGNED TFT-LCDs

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Fujitsu has developed several types of vertically aligned TFT-LCD: with protrusion; with photo-alignment; and with comb-shaped electrodes. The protrusion-type TFT-LCD has the best balance of specifications and is in mass-production. It has a transmittance of 5% for a 15-inch XGA LCD, a response of 25 ms ($\tau_{on} + \tau_{off}$), and a contrast ratio of over 400. The photo-aligned type gives highest transmittance (7.5%) with dual domains. The lamp for UV irradiation can be a tube type and non-polarized UV is possible. We think it is a good candidate for notebook-type applications. The comb-shaped electrode type has the fastest response of better than 17 ms for any gray-scale switching. We think it is a good candidate for video applications.

1. INTRODUCTION

Liquid crystal displays (LCDs) are now finding a wider range of applications. In addition to devices such as cellular phones, personal computers, and PDAs, they are being applied to audiovisual equipment including wide-screen television sets. The primary advantages prompting the expanded application of LCDs have been their space- and power-saving features. Further expansion of these devices will depend on the progress made in solving problems in their display characteristics. The performance of a display device is usually evaluated in terms of its contrast, brightness, viewing angle, color reproduction, resolution, and response speed. Among these parameters, the conventional LCD has a very tough time at achieving a superior viewing angle, brightness, and response speed [1–31]. We have developed three types of VA LCDs; VA TFT-LCD with protrusions offers a well-balanced specification [21,26,29,30], VA TFT-LCD with photo-alignment offers a high transmittance [19,20,23,30], VA TFT-LCD with comb-shape electrodes and oblique electric field offers a fast response [27,28].

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2. VA TFT-LCD WITH PROTRUSIONS

A new alignment control technology with protrusions has been developed. The principle is illustrated in Figure 2-1. Instead of processing the surface of alignment layer, as done in the conventional approach, this technology adopts the new concept of processing the underlying structure beneath the alignment layer. Structures installed partly beneath the alignment layer form protrusions. When the voltage supply is turned OFF, most of the liquid crystal molecules align themselves vertically to the substrate, but those positioned above the protrusions incline slightly towards the substrate due to the slope of the protrusions beneath them. When the voltage is turned ON, the molecules on the sloped protrusions initially start tilting in the direction shown by the arrow in Figure 2-2, and then the molecules in the regions without protrusions are affected by the tilting molecules and align themselves in the same direction. In this way, stabilized alignment is attained in the entire pixel. In other words, controlled alignment is achieved over the entire display area starting from the protrusions.

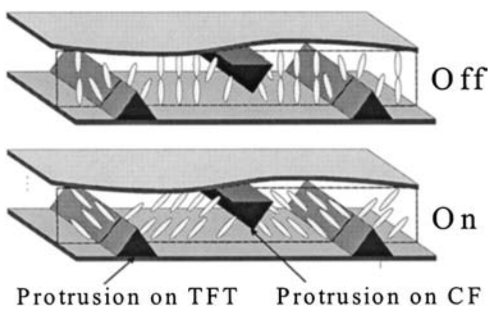


FIGURE 2-1 Principal structure of new LCDs.

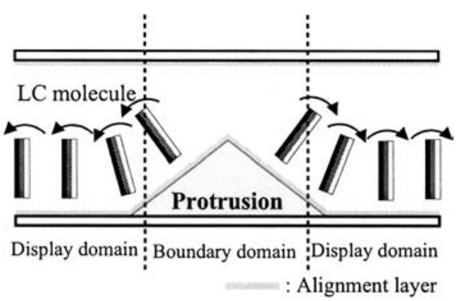


FIGURE 2-2 Tilting of LC molecules.

Figure 2-3 illustrates alignment control by a combination of electrode slits and protrusions on color filter (CF) substrate. As can be seen from the figure, the TFT substrate has no protrusion formed on the surface, and parts of the ITO pixel electrode are etched off (electrode slits). When voltage is supplied, a deformed electric field (diagonal electric field) is generated in the vicinity of the individual slits, providing field distribution and alignment control of the liquid crystal molecules similar to those attained when protrusions are installed. The simultaneous formation of slits with ITO pixel electrodes can eliminate the need for additional processes.

Figure 2-4 shows the micro-photograph of the real TFT pixels with protrusions and slits of ITO. Slits are fabrication in ITO electrode in stead of protrusions on ITOs. The liquid crystal molecular alignment is divided into four domains, North-East, North-West, South-East, South-West.

Actual photograph of the pixel when the voltage is applied (white state) is shown in Figure 2-5. The big disclination lines are seen at specific position near the pixel edge. This results in the reduced transmittance of the multi-domain vertically aligned (MVA) panels. The tilted directions of the

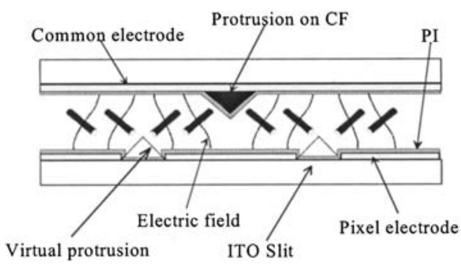


FIGURE 2-3 Alignment control by electrode slits and protrusions.

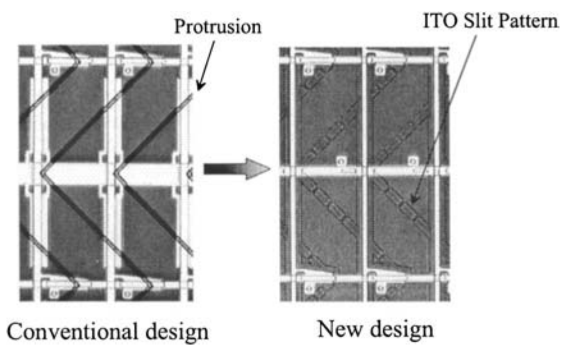


FIGURE 2-4 Real pixel design with protrusions or slits.

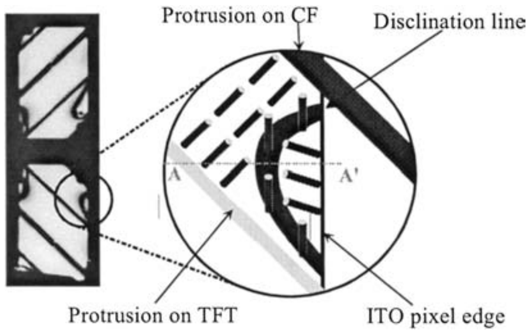


FIGURE 2-5 Actual micro-photograph of pixel and alignment.

LC molecules are also illustrated in Figure 2-5. The tilted directions are opposite way for domains divided by the disclination line and the cause can be estimated by the edge field effect of the pixel ITO.

To remove this disclination line, we put additional protrusion on the counter electrode which is placed just in front of the pixel edge (Figs. 2-6, 7).

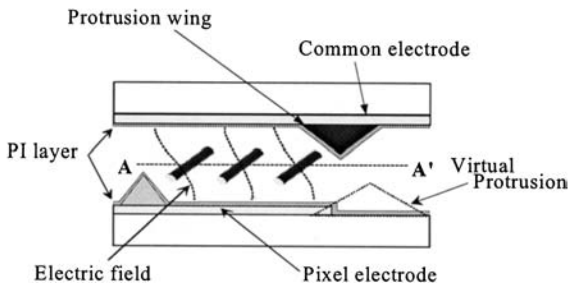


FIGURE 2-6 Cross sectional view of protrusion wing.

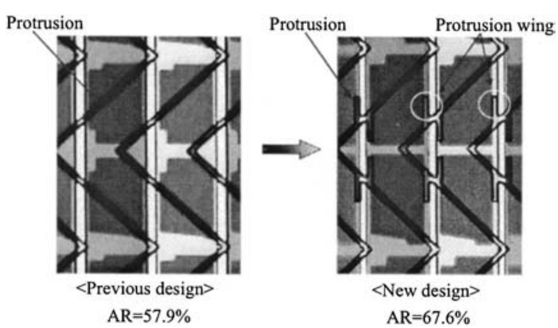


FIGURE 2-7 Previous and new design with protrusion wing.

The newly adopted protrusion is called protrusion wing and the ability to control the tilted direction is much bigger than that of the edge field effect due to distorted electrical field.

Figure 2-8 shows the newly designed columnar spacer panel. The layers of Red, Green, and Blue resin filters are stacked only on the pixel borders to minimize the leakage of light rays from the borders (stacked RGB color filters prevent the transmission of light rays). This eliminates the need for black matrix required in the existing manufacturing processes. In addition, a protrusion is formed on the color filter-stacked point to provide a cell spacer and create a cell gap. This protrusion acts as a spacer and an alignment controller. This approach eliminates the black matrix forming process and spacer distributing process, simplifying the process on the whole. Figure 2-9 shows SEM photograph of spacer. The protrusion layer stacked on ITO enables to avoid an electrical short between CF and TFT substrates and to keep an appropriate cell-gap.

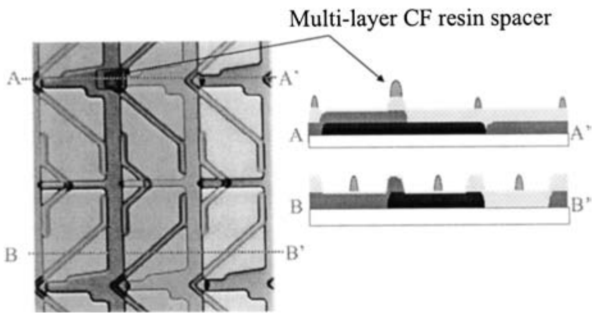


FIGURE 2-8 Multi-layer color filter resin spacer.

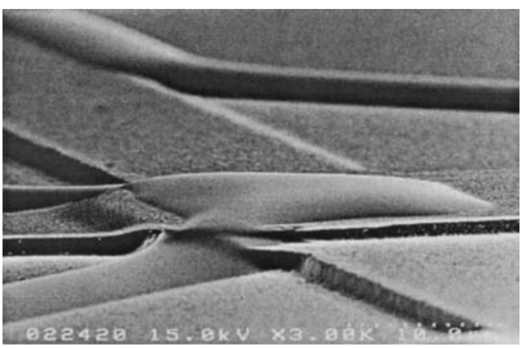


FIGURE 2-9 SEM photograph of spacer.

It is pointed out that the switching characteristic from black to dark gray levels is disadvantageous (Fig. 2-10). Figure 2-11 shows LC switching mechanism of MVA-LCDs. The direction of the vertically aligned LC molecules is determined by protrusions on CF substrates or by ITO slits on TFT substrates. In this technology, when a voltage is applied, the LC molecules around the protrusions tilt at first because they initially have a tilted alignment due to the slope of the protrusions and also the oblique electrical field created around them is consistent with the initial tilting. We call this situation as "partial control" in Figure 2-11. Subsequently, the remaining LC molecules between the protrusions and the ITO silts gradually tilt to the same direction from both sides. This is the propagation of LC alignment. Consequently, in conventional MVA mode, the response time for turning on contains this extra propagation time or sleeping time.

Figure 2-12 illustrates the technology, in which ITO pixel electrodes have a jagged shape and a main fringe structure at the center. The LC

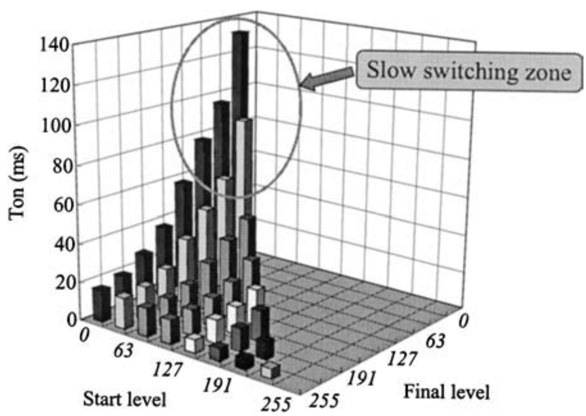


FIGURE 2-10 Response characteristics of conventional MVA.

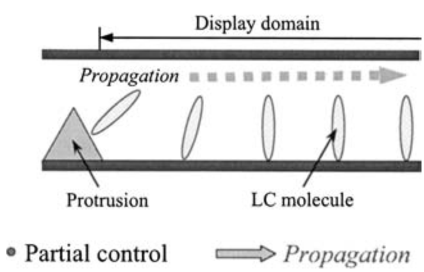


FIGURE 2-11 LC molecular switching.

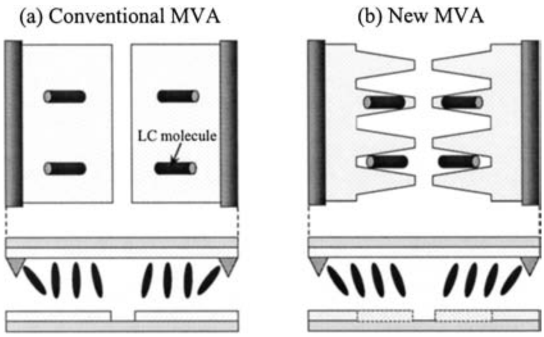


FIGURE 2-12 New pixel design and LC molecular tilt.

molecules tend to tilt by the deformation of the electric field around the jagged ITO pattern. As the minutely patterned ITO cover most of the display domain area, we are able to obtain a remarkable improvement in response time by reducing the propagation time. Figure 2-13 shows the high-speed camera photograph of the response from black to a grey-scale level. With the jagged shape electrode, the transmittance changes almost simultaneously in the whole pixel area.

Figure 2-14 shows the measured response characteristics for the new MVA panel in comparison with the conventional MVA and a Super-IPS [10] panel. The starting level of the switching is black, which is the weakest case in the MVA-LCDs. The response speed to 20% of the white transmittance is about three times as fast as that of the conventional one.

Figure 2-15 shows the fabricated 17″ diagonal wide-screen TFT-LCD.

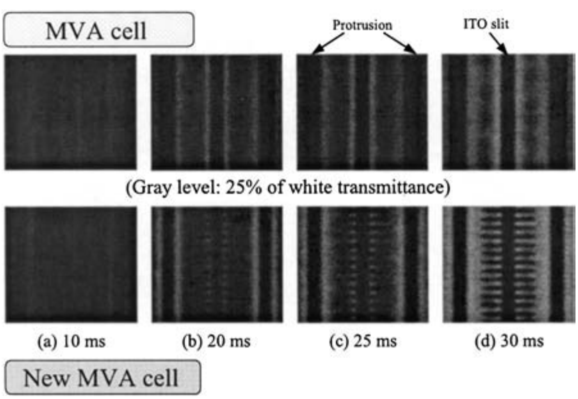


FIGURE 2-13 High-speed camera photograph of switching.

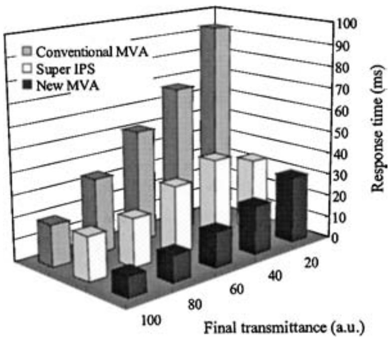


FIGURE 2-14 Response characteristics improved.

FIGURE 2-15 17W inch diagonal TFT-LCDs.

This MVA mode has balanced specification; high contrast ratio, rather fast response speed, sufficient transmittance for monitors.

3. VA TFT-LCD WITH PHOTOALIGNMENT

We have developed TFT-LCDs with high transmittance with photo-alignment technology. We think that VA-TFT LCD can be used as screens for note-book type PCs.

Figure 3-1 shows the photo-alignment principle. Polyimide layer with alkyl side chain is irradiated with unpolarized UV light. A part of side alkyl chain is deformed and the liquid crystal molecules are aligned by the residual alkyl-side chains.

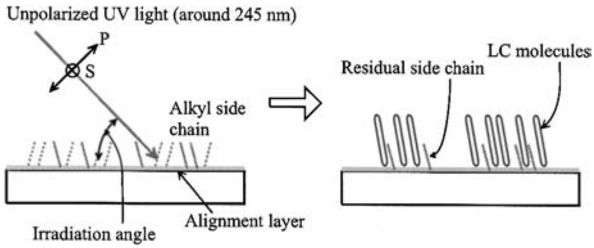


FIGURE 3-1 Photo-alignment principle.

Figure 3-2 shows the pretilt angle of the fabricated cell vs. UV irradiation energy characteristics of the fabricated cell. The pretilt angle decreased as the UV irradiation energy increased. Figure 3-2 also shows photographs of the fabricated cell between a pair of crossed polarizers with an intermediate voltage. When the UV irradiation energy was too low, black spots appeared around spacers. When the UV was irradiated in excess, defects appeared parallel to the LC filling direction. With an appropriate UV dosage, no such black spots appeared and the tilt angle of the liquid crystal was around 89 degrees.

Figure 3-3 shows the response speed of fabricated LC panel. The response time between several gray scale level were almost the same or rather faster than the LC panel with rubbing technology.

Next, we tried to develop dual-domain TFT-LCDs. Figure 3-4 shows the UV irradiation system. We used a tube-type fluorescent lamp to irradiate the surface of the vertical alignment layer with unpolarized UV. Since the lamp house is small, the equipment size is quite small and inexpensive.

Figure 3-5 shows how we irradiated with UV light through an optical mask and shows the cross sectional panel configuration. The aperture of the optical mask is less than half of the pixel pitch. The UV is irradiated

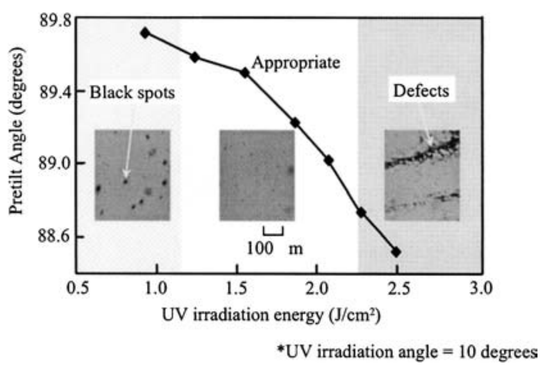


FIGURE 3-2 UV irradiation and pretilt angle.

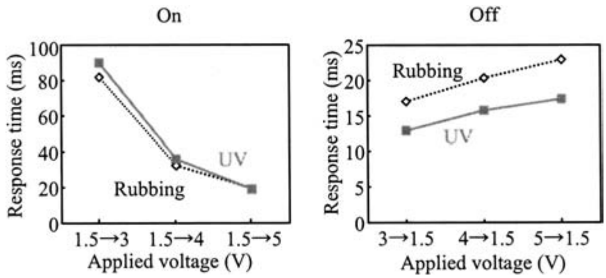


FIGURE 3-3 Response time.

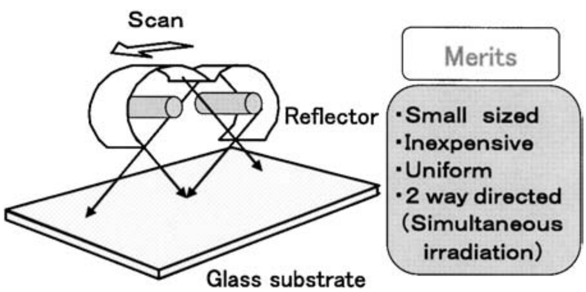


FIGURE 3-4 UV irradiation system.

through this aperture from two directions simultaneously. By scanning the UV lamp, we can irradiate at the same dose over the whole area. After irradiating the surface of a pair of substrates, we stacked and filled them with liquid crystal with negative dielectric anisotropy. We fabricated protrusions on the CF substrate at the pixel centers to produce dual-domain TFT-LCDs.

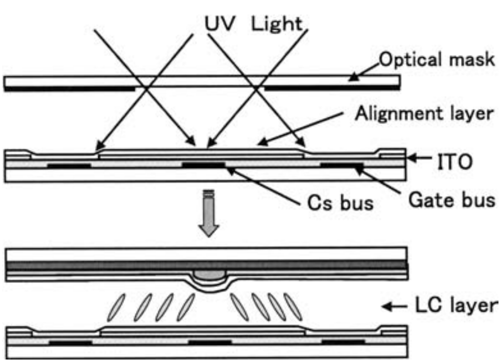


FIGURE 3-5 How to irradiate UV through an optical mask.

With prototype TFT-LCDs, disclinations appeared parallel to the gate bus line or CS (subsidiary capacitance) bus lines (Fig. 3-6). This disclination is due to distortion of the optical mask. If the optical mask is distorted by 20 μm, the gap between the mask and LCD substrate changes and the irradiation area can move by 20 μm. When the surface of the alignment layer is irradiated twice with UV light, the anchoring of the alignment layer is damaged and the disclinations appear. To solve this problem, we narrowed the aperture of the optical mask to less than half the pixel pitch so that the alignment cannot be irradiated twice at one position and achieved alignment without disclinations.

There appeared other disclinations (Fig. 3-7) along the data bus lines caused by the oblique electric field from the data bus lines. Figure 3-8 shows the cross section alogn line X in Figure 3-7. We fabricated subsidiary protrusions parallel and along the bus lines to reduce these disclinations

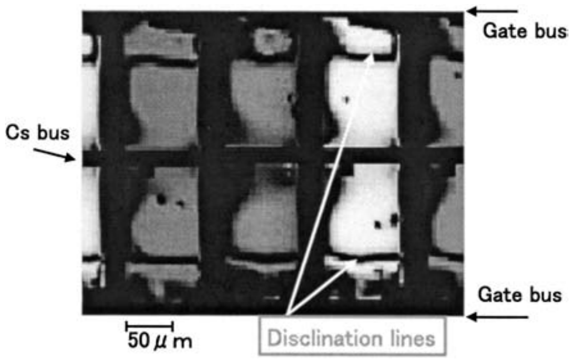


FIGURE 3-6 Disclination due to distortion of optical mask.

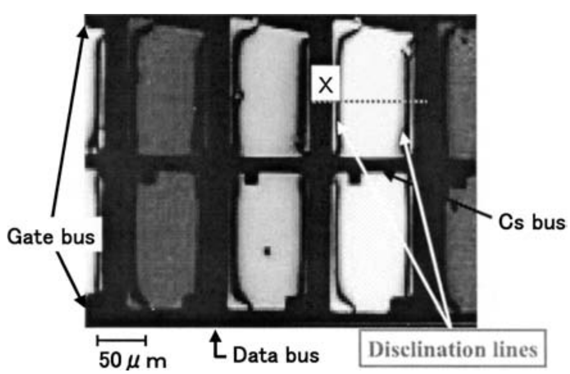


FIGURE 3-7 Disclination due to oblique electric field from data bus.

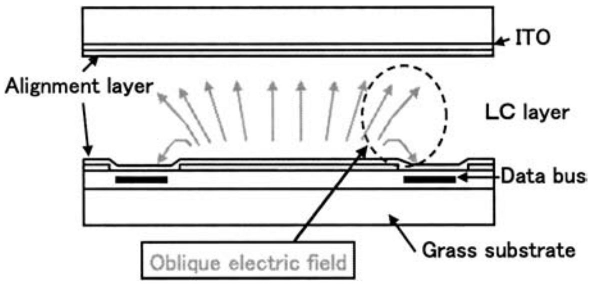


FIGURE 3-8 Cross section along line X in Figure 3-7.

(Figure 3-9). Since the oblique electric field around and from the data bus line (shown in circle in Figure 3-8) is suppressed by the subsidiary protrusions, the disclinations are reduced.

Figure 3-10 shows the TFT pixels. There is no disclination and the transmittance is high. Figure 3-11 shows an example of the display of the

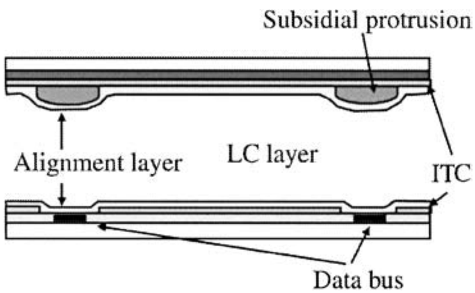


FIGURE 3-9 Subsidial protrusion to reduce disclination.

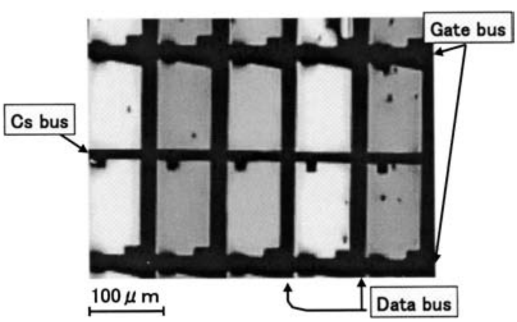


FIGURE 3-10 Micro-photograph of new pixel.

FIGURE 3-11 15 inch diagonal TFT-LCD.

TABLE 3-1 Specification

Size	15″
Pixels	XGA (1024 × 768)
Transmittance	7.4%
Color gamut	54% (NTSC)
Contrast ratio	500:1
Response time	25 ms
Viewing angle	> 160 degrees

fabricated 15-inch diagonal XGA TFT-LCD and Table 3-1 shows the specifications. The contrast ratio in the normal direction is better than 500 and the transmittance is 7.4%. This transmittance is twice that of IPS LCD [9,10], 1.5 times that of conventional MVA-LCD [21] and 1.1 times that of TN-LCDs with Wide-View film [14]. In this case, we used a color filter layer to achieve a wide color gamut (54% of NTSC). We think this newly developed TFT LCD is excellent candidate for the display of notebook computers with multi-media application.

4. VA TFT-LCDS DRIVEN BY OBLIQUE ELECTRIC FIELD

We have developed Vertically Aligned TFT-LCDs driven by oblique electric field which has sufficiently fast response speed for any gray-scale switching.

Figure 4-1 shows the cross section of the LCDs. The LCD is composed of interdigital electrodes like the IPS mode, a transparent electrode (ITO) on the CF substrate like the MVA-LCD, and a dielectric layer on the ITO layer. It contains liquid crystal with positive dielectric anisotropy and is initially

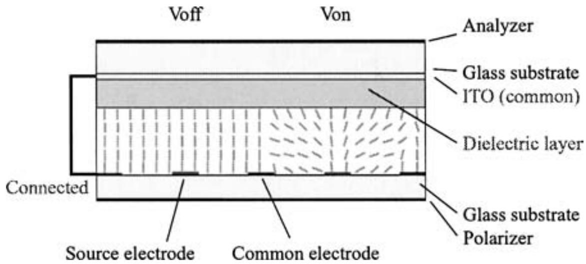


FIGURE 4-1 Cross sectional view of newly developed LCDs.

aligned vertically. A pair of crossed polarizers are stacked on the substrates. Because the new LCD has an ITO electrode inside the LC cell, it does not suffer from the electrostatic-charge problem of the IPS mode.

Figure 4-2 shows a microphotograph of VA-IPS (without ITO electrode and dielectric layer on CF substrate) and the new LCD. There are disclination lines between the source and common electrodes in case of VA-IPS. However, the new LCD mode has no disclination lines and the screen brightness is higher. When voltage is applied, the electric field from the source electrode extends to both the common electrodes on the TFT and CF substrates (Fig. 4-3). Since the electric field is asymmetrical, the LC molecules are parallel to the electric field asymmetrically and there is no disclination.

Figures 4-4 show the effect of the dielectric layer on ITO. Without the dielectric layer, the line of equipotential is only in the LC layer, so the direction of the field is almost perpendicular to the glass substrate. The LC molecules are not inclined parallel to the substrate, resulting in a low brightness level. With the dielectric layer, the line of equipotential extends

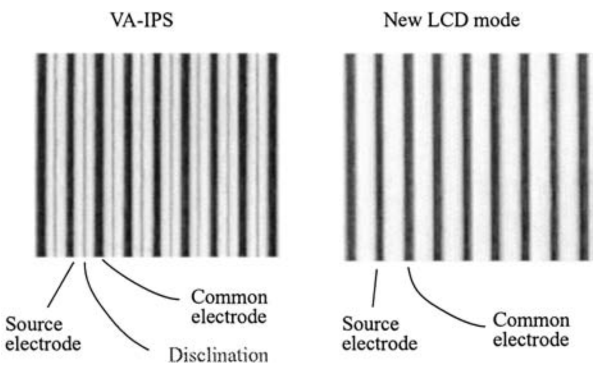


FIGURE 4-2 Microphotograph of VA-IPS and new LCD mode.

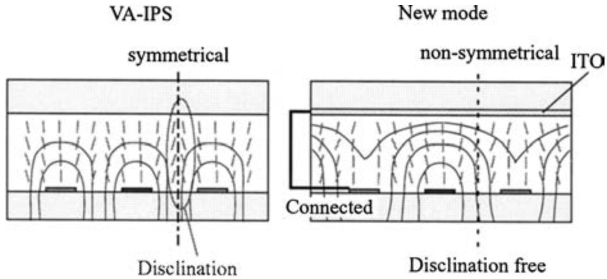


FIGURE 4-3 Electric field with VA-IPS and new LCD.

to the dielectric layer. The ratio of the electric field parallel to the substrate is higher, so more LC molecules are parallel to the substrate, resulting in higher brightness.

Figure 4-5 shows the measured response characteristics of the new LCD. The x- and y-axes show the gray scales before and after switching and the z-axis shows the rising and decaying response times. The response time for black-and-white switching is 13 ms for rising (from 0th to 63rd gray level) and 4 ms for decaying (from 63rd to 0th gray level). The slowest response time for gray-scale images was 17 ms for rising (from black (0th) to gray (16th)) and 11 ms for decaying (from white (63rd) to gray (48th)). Almost every response time is shorter than the frame period (16 ms) and is sufficient for multimedia use.

Figure 4-6 shows the calculated electric field when 2 V and 10 V are applied for a dark-gray image and white image respectively. When 2 V is applied, only the liquid crystal around the source electrodes is switched and the electric field is 0.325 V/m. When 10 V is applied, the liquid crystal of the whole area between the electrodes is switched and the electric field is 0.765 V/m. The lower voltage (2 V) is 20% that of the higher voltage

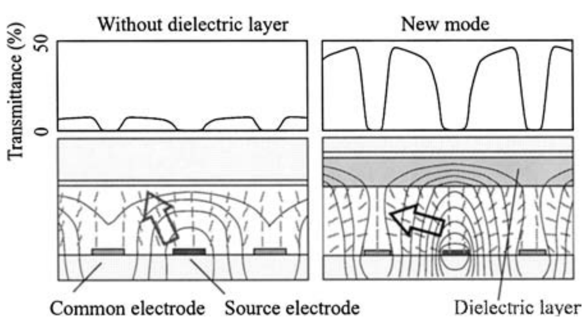
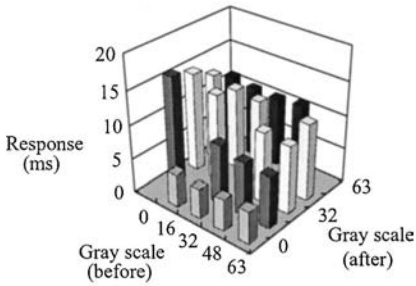


FIGURE 4-4 Effect of dielectric layer on ITO layer.



Gray-scale levels	0	16	32	48	64
Transmittance (100=white)	0.4	5	30	75	100

FIGURE 4-5 Response speed.

(10 V), but the electric field is almost half. In the case of an LCD switched by a parallel field to the substrate, the movement of the LC molecules is determined by the strength of the electric field, not the applied voltage. For example,

$$\tau_{\text{on}} = \gamma d^2/\{(A^2 - 1)\pi^2 K\}$$

γ: viscosity, d: cell gap, A: E/Eth, E: Electric Field, K = K1 = K3 (for simplifying the equation.)

The small difference in the electric field with low and high driving voltages explains the small difference in the response between various gray-scale levels.

Figure 4-7 shows a schematic pixel structure of fabricated TFT-LCDs. Half the comb-shaped electrodes have an azimuth angle at 45 degrees, and the other half have an azimuth angle at 135 degrees, so the LC molecules incline in four directions.

The first sample had lower transmittance than expected. There appeared dark regions in the aperture areas. Figure 4-8 shows the microscope photograph of the pixel whose area is shown in Figure 4-7 by dotted line. As the electrodes are kinked at an acute angle, the electric field

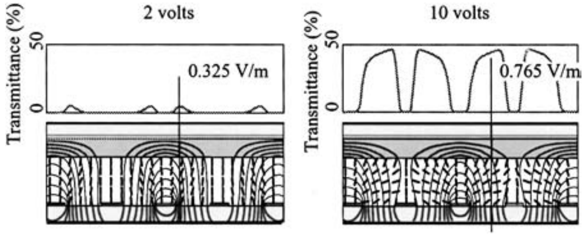


FIGURE 4-6 Electric field and reason of the fast response.

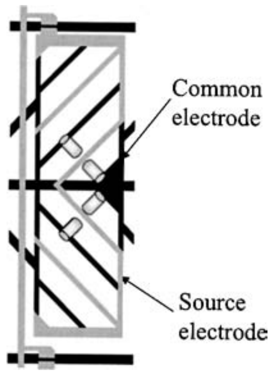


FIGURE 4-7 Schematic pixel structure of fabricated TFT-LCDs.

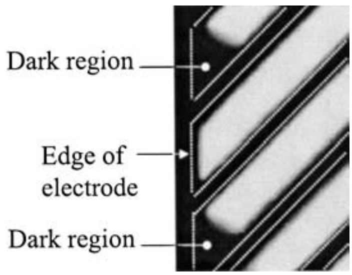


FIGURE 4-8 Microphotograph of pixel.

is not applied on these regions and the liquid crystal molecules are not inclined.

We developed wing-shaped electrodes (Fig. 4-9). Some source electrodes were extended over common electrodes and common electrodes were

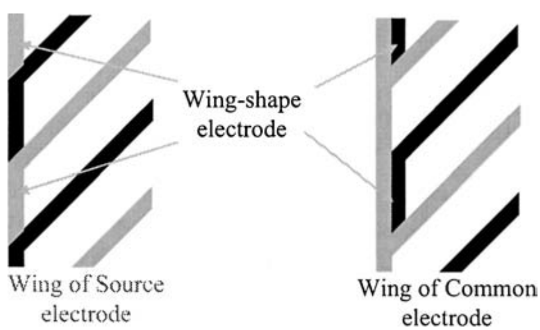


FIGURE 4-9 Wing-shaped electrode.

extended along source electrodes. Figure 4-10 shows the electric field when a common electrode or a source electrode is extended to apply electric field on the liquid crystal layer. The common electrodes should be extended longer than the source electrodes because the common electrodes are located beneath the source electrodes.

We fabricated the new LCD with the wing-shaped electrodes. Figure 4-11 shows the microscope photograph of the TFT-LCD with the new pixel structure. There are no dark regions inside the aperture areas.

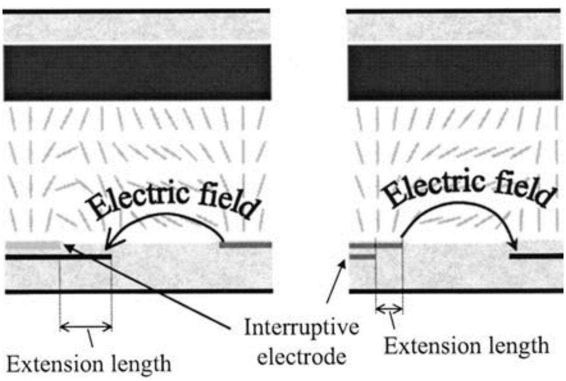


FIGURE 4-10 Cross section of wing-shape electrodes.

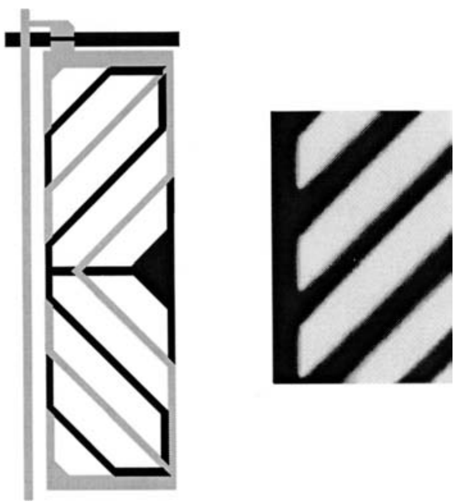


FIGURE 4-11 Electrode design and microphotograph of pixel.

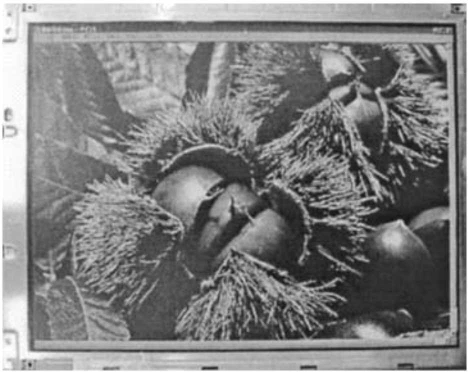


FIGURE 4-12 15 inch diagonal TFT-LCD.

TABLE 4-1 Specification

	New LCD	VA-IPS
Display area	15″diagonal	⟵
Number of pixels	XGA (1024 × RGB × 768)	⟵
Viewing angle	> 160 (up-down)	⟵
(CR > 10, no reversed image)	> 160 (right-left)	⟵
Response time (black/white)	17 ms($\tau_r + \tau_d$)	40 ms
(slowest between gray scale)	17 ms	—
Transmittance	3.5%	< 1%
Brightness	200 cd/m^2	—

Figure 4-12 shows the fabricated 15 diagonal XGA TFT-LCDs and Table 4-1 shows the specifications. It has a wide viewing range, fast response and good light transmittance, making it a potential candidate for use in video applications.

5. SUMMARY

Three types of vertically aligned TFT-LCDs are reviewed.

VA TFT-LCD with protrusion has balanced specification. The transmittance is sufficiently high for monitors, and the response speed is comparable with TN-LCDs, and the contrast ratio is so high (500). It has been manufactured and used for various size of LCD monitors.

VA TFT-LCD with photo-alignment has 1.5 times higher transmittance than that with protrusions. It is a great candidate as a screen for notebook type PCs.

VA TFT-LCD with interdigital electrode has fast response for any gray-scale switching. It is a great candidate as a screen for TV application.

The VA TFT-LCDs can be used for any application; monitors, TVs, note-type PCs, cellular phone, PDA, Auto-motive, Avionics, Digital video etc. We think that the future of the VA TFT-LCDs are so bright.

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