An overview of product issues in wide-viewing TFT-LCDs

Seung Hee Lee
Seung Ho Hong
Jin Mahn Kim
Hyang Yul Kim
Jung Yeal Lee

Abstract — Several TFT-LCD devices exhibiting high image quality have been developed and commercialized, overcoming the narrow viewing-angle characteristics of conventional twisted-nematic (TN) devices. Nevertheless, no single device dominates large-sized TFT-LCDs. In this paper, the product issues of existing LC devices related to manufacturing process and performance are discussed.

Keywords — *TFT-LCDs, wide viewing angle, product issues, manufacturing process and performance.*

1 Introduction

In liquid-crystal displays (LCDs), the LCD mode that determines the initial alignment of the LC molecules and the field direction determines the image quality and manufacturing processes of the display. Therefore, developing a LCD mode with high performance is the key factor in obtaining a TFT-LCD with high image quality and low manufacturing cost. Recently, several new devices such as discotic film-compensated TN, Advanced Super-View (ASV),[1-3] in-plane switching (IPS),[4,5] fringe-field switching (FFS),[6-10] multi-domain vertical alignment (MVA),[11,12] patterned VA (PVA)[13] as well as other devices were developed, in which most of them are already commercialized. The TFT-LCDs with these modes demonstrate a wide-viewing angle that overcomes an intrinsic problem of the twisted-nematic (TN) mode, and have the potential to replace the CRT as monitors as well as televisions. In terms of image quality, the new devices are comparable to CRTs except for the response time. Nevertheless, the new devices with new concepts decrease the production yield and thus increase manufacturing cost, compared to that of the conventionally well-established TN device. At present, the cost of LCD fabrication is one of the major reasons why they have not replaced CRT displays more rapidly than expected. In this paper, a discussion of each device in terms of image quality and manufacturing issues is made to understand what the difficulties are in the manufacturing processes and image qualities of the devices, based on our experiences and that described by others in published papers.

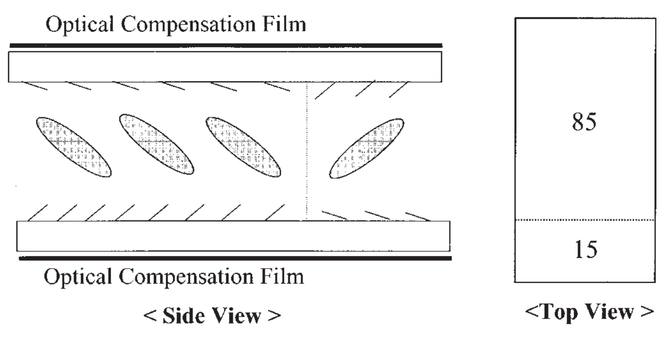


FIGURE 1 — Divided TN domain for one pixel with different area ratios using "Super V".

2 Wide-viewing devices

2.1 Film-compensated TN and Advanced Super View (ASV) displays

In the twisted-nematic (TN) mode, the LC molecules are rotated 90° from the top to the bottom substrate and a vertical field is used. In this way, the twisted LC molecules play a role similar to an optical rotator, showing high light efficiency. The TN mode is well established in design concept as well as in production. Consequently, the production yield is very high. However, the TN mode features a narrow viewing angle. In the film-compensated TN device, the film reduces the leakage of light in the off (dark) state in oblique viewing directions, thus improving the contrast ratio at off normal directions. Nevertheless, it still shows a strong viewing-angle dependence on gray scale, particularly in the vertical direction, since the LC director tilts up only in one direction by a vertical field. In order to overcome such a viewing-angle dependence, the divided domain of one pixel with an area ratio of 85:15 and with different tilt angles on the top and bottom substrates (referred to as "Super V") has been suggested, as shown in Fig. 1. This improves the viewing angle in the vertical direction, although it is still not at a satisfactory level. Furthermore, the product shows a non-

Revised version of a paper presented at the first International Display Manufacturing Conference held on September 5-7, 2000 in Seoul, Korea.

The authors are with Hyundai Display Technology, San 136-1, Ami-ri, Bubal-eup, Ichon-si, Kyungki-do, 467-701, Korea;
telephone +82-31-639-6452, fax -6458, 1sh1@hydis.com

S. H. Lee is with Chonbuk National University, Duckjindong 664-14, Chonju, Chonbuk, 561-756, Korea.

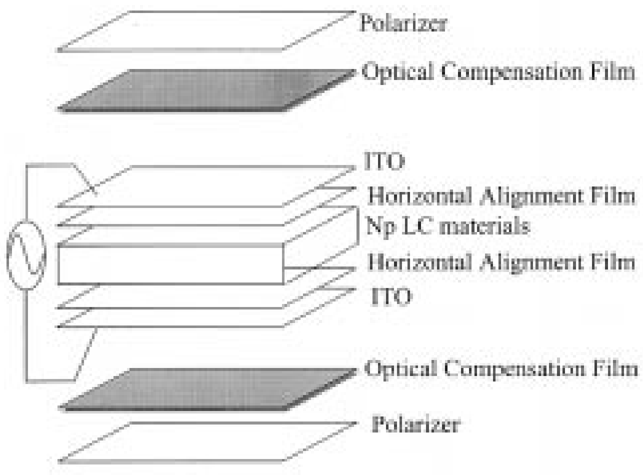
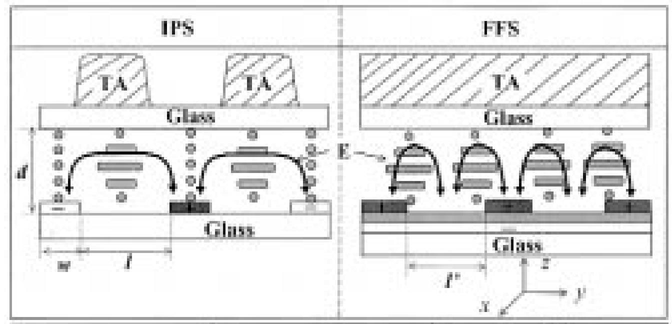


FIGURE 2 — Cell structure of the ASV.



	IPS	FFS
l / d	>1	<1 or 0
l / w	>1	<1 or 0
Field	E_y	E_y, E_z
Electrodes	Metals or ITO	ITO

FIGURE 3 — Features of the IPS and the FFS devices.

uniform light luminance at dark state due to a non-uniform retardation value of the discotic film. Moreover, manufacturing issues still exist, since the device requires a UV-irradiated process or mechanically double-rubbing process with surface-treated ITO when the divided-domain device is fabricated. In 1999, Sharp Co. reported a new device referred to as "Advanced Super View (ASV)" that had a fast response time of 16 msec and ultra-high-aperture technology.[3] The cell structure with homogeneous alignment of the LC molecule with positive dielectric anisotropy (N_p) at the initial state is shown in Fig. 2, but the details of the switching mechanism are still unknown. Conclusively, the device associated with the TN mode has advantages of high light efficiency and ease of design of the panel, but the viewing angle is limited and the manufacture of a divided domain is rather difficult to accept in conventional lines because of the cost of the extra lines after coating of the alignment layer. The cost-up factor in the device is due to the use of compensation film.

Recently, Sharp Co. has reported a new type of ASV display with vertical alignment of the LC molecule at the initial state.[14] The device shows high electro-optical performance, but how the LC director actually tilts down in a 360° direction due to an electric field has not been explained in detail. Therefore, manufacturing issues cannot be discussed at this time.

2.2 IPS and FFS

A comparison of the electrode structure of one pixel between the IPS and the FFS devices is shown in Fig. 3. The IPS and FFS devices utilize in-plane switching and fringe field to drive homogeneously aligned LC molecules to rotate, respectively. Both devices are known to exhibit wide-viewing angle owing to the in-plane rotation of the LC director. In the IPS array process, the pixel and common electrodes consist of gate and source/drain metals and exist only in the bottom substrates with patterned electrodes in a slit format. The device does not use ITO. However, we could find several IPS panels with ITO coated in the active or pad area, so that the device requires a five or seven mask process, depending on the type of thin-film transistor (TFT) used, similar to the conventional TN process. Furthermore, the surface of the bottom substrate has a depth difference due to the thickness of the electrodes which is at least more than 1000 Å, and so the device requires planarization of the array substrate in order to achieve good alignment of the LC molecules by rubbing. In the cell process, both devices require a rubbing process and the same production line just like the conventional one. However, the surface of the color-filter (CF) substrate is not an ITO layer. Instead, an overcoat (OC) organic layer is used for the planarization of the CF substrate. However, this causes a coating issue between the organic alignment layer and the OC, which lowers the yield. Therefore, a careful cleaning process or proper selection of materials is necessary in order to solve the problem. Another issue is the rubbing sensitivity. After rubbing the alignment layer, the groove is made in the rubbing direction on the surface of the alignment layer. However, the depth of the groove by cloth rubbing is not perfectly uniform, that is, it is dependent on the position of the panel. In the TN device, the LC director tilts upward due to an applied voltage, so that nonuniformity of the groove weakly affects the LC molecules from tilting up. However, in the IPS device, the LC director rotates in plane so that the nonuniformity of the groove causes the LC molecules to rotate nonuniformly, depending on the position. As a result, the luminance is not uniform, particularly for gray levels. In this device, much more careful rubbing than that for a TN device is required. In the FFS device, unlike in the IPS device, only the pixel electrodes are patterned in a slit form, forming storage capacitance in the light transmitted area (TA). In fact, there are two approaches to fabricate the FFS device; that is, the pixel and common electrodes are patterned with a distance (l) or only the pixel electrodes are

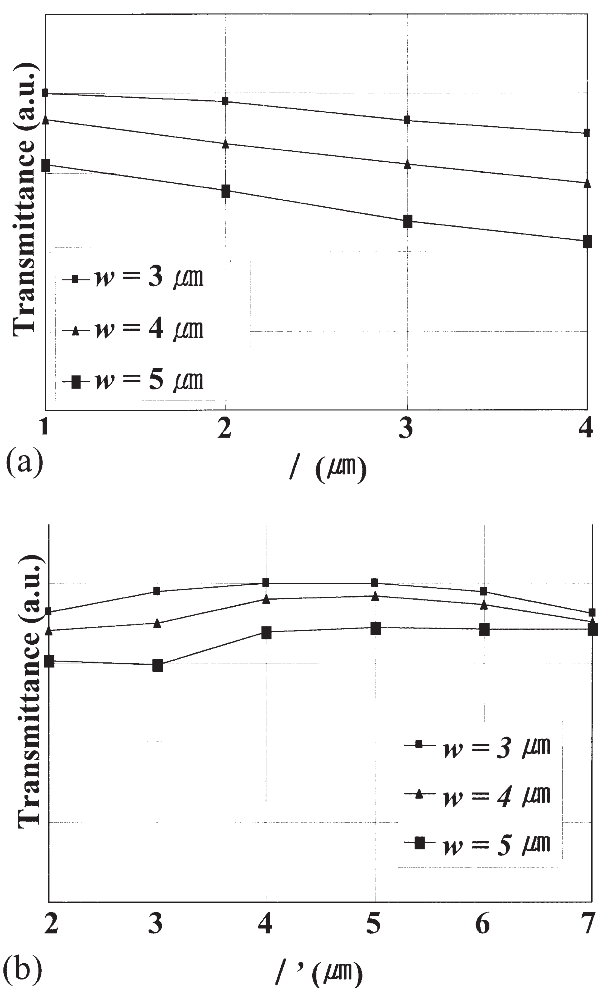


FIGURE 4 — (a) l and (b) l' – dependent transmission curves for several electrode widths.

patterned with a distance (l') between them. We have compared the process sensitivity for both cases, as shown in Fig. 4. The latter case has a wider process margin, higher transmission, and lower driving voltage than those of the former. In both devices, the electrodes should be transparent, since the LC director performs light modulation above the electrodes. In view of the number of masks required to manufacture the array substrate, in addition to the conventional five-mask process, one more mask for the ITO layer is added. Nevertheless, the FFS device does not require the planarization process for the bottom substrate in order to achieve good alignment of the LC, since the bottom surface has a roughness of only 400 Å. The coating issue for the alignment layer on a color-filter substrate is the same as for the IPS one. For the electro-optic characteristics, the light efficiency of the FFS device is about 90% of that for the TN device, overcoming the long-standing problem that has existed in the IPS device. In the IPS device, the voltage-dependent transmittance curve is mainly dependent on the cell gap and the distance between electrodes. So whenever the size of pixels, *i.e.,* resolution of the display, changes, the several cell design parameters of the new display must be adjusted. However, in the FFS device, only a change in the number of pixel electrodes is needed. Therefore, the FFS device has a greater advantage when designing products with various resolutions. Furthermore, when fabricating a two-domain IPS (Super-IPS) device, the decrease in aperture ratio is inevitable. However, for the two-domain FFS (Ultra-FFS) device, the aperture ratio can be kept at the same level as that of the single-domain FFS device. Conclusively, both devices exhibit high performance, but the process sensitivity when manufacturing a cell is increased compared to that of a TN device, and thus for both devices to be more competitive, the production yield needs to be improved.

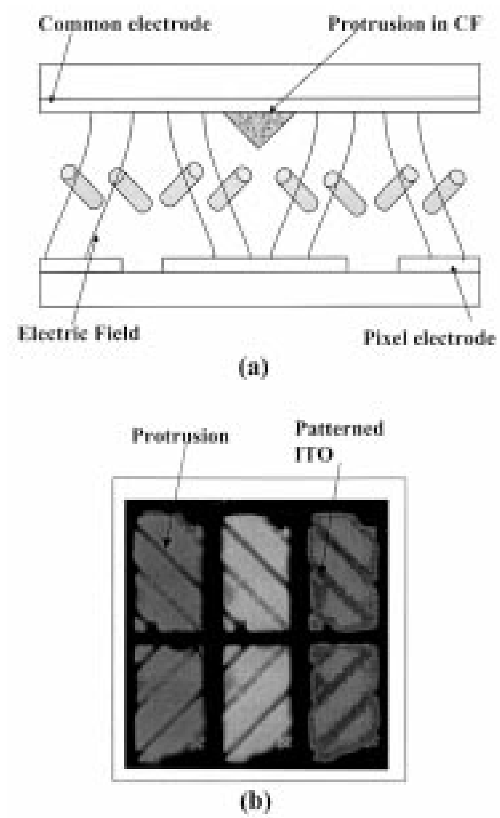


FIGURE 5 — (a) Cross-sectional and (b) top views of the MVA device with protrusion and patterned ITO.

2.3 MVA

In the MVA device, the LC molecules are aligned at a slightly tilted angle from the vertical because of a protrusion on the top substrate, under crossed polarizers. When a voltage is applied, an oblique field instead of a vertical field caused by the protrusion on the top substrate and the slit patterned ITO on bottom substrate is induced to drive the LC molecules to tilt down in four directions. Figure 5 shows side and top views of the one pixel. As can be seen, the protrusion and patterned ITO exist alternately. The optical compensation film to suppress light leakage of the dark state at off-normal directions is attached to the polarizer. The improvement in the MVA device made by Fujitsu Co. has been made a big difference. The MVA device had protrusions on the top and bottom substrates of the initial product, which requires two more masks than for conventional TN. But more recent devices shows that the protrusion exists only on the top substrate and the patterned ITO on the bottom substrate replaces the protrusion. Furthermore, the device utilizes red, green, and blue color-filter layers and overcoat resins as a spacer, a protrusion, and a shielding layer to prevent light leakage from the area between the data and gate lines. As a result, the multi-layers in the MVA device eliminate the need for a black matrix as well as for bead spacers. The device is the first transmissive monitor display without a black matrix (BM) while still demonstrating a contrast ratio of more than 200:1. From a manufacturing viewpoint, the optimized size, location of the protrusion, and a proper slit pattern for ITO are key factors in stabilizing the dynamics of the LC director when a voltage is applied. In the device, the electro-optic characteristics are sensitive to the structure of the protrusion and the patterned ITO and materials; that is, the smaller the distance between protrusions, the faster the response time, but this results in a lower light efficiency. And the response time also strongly depends on how the LC director tilts downward in various directions from vertical alignment. This indicates that the shape of the protrusion is very important in obtaining high image quality, and the existence of a bead spacer might hurt the LC dynamics. Therefore, replacing the bead spacers by column spacers on color filter might be unavoidable. In addition, the LC dynamics also depend on the anchoring energy of the vertical alignment layer as well as dielectric constant of the protrusion. Further, it is dependent on the alignment accuracy of the assembly of a panel. In view of the LC dynamics, the MVA is also a new device, requiring careful optimization of the various parameters. However, once it is optimized, the dynamics are stable enough. Again, from a manufacturing viewpoint, the new MVA device does not require a rubbing process and spraying of the spacers. One mask for the protrusion on the color-filter side is added, but one mask is eliminated by not using a black matrix, so the total number of masks is the same as for the conventional TN device. One disadvantage in the cell process is an increase in the LC filling time because the nematic rod-like LC should align perpendicular to the substrate while filling, and also the protrusion disturbs the flow of filling. This can be overcome by filling the LC at a temperature higher than room temperature since the viscosity of the LC drops at high temperature. Otherwise, the filling time will increase much more than three times than that of the TN device. But new filling equipment solves, to some degree, problems such an intrinsic problem in the VA device. The major disadvantage of the device is the increase in the cost of materials, such as CF, negative LC, the vertical-alignment layer, and compensation film. Therefore, a high production yield to compensate for the material cost is absolutely necessary in order for the MVA device to be competitive.

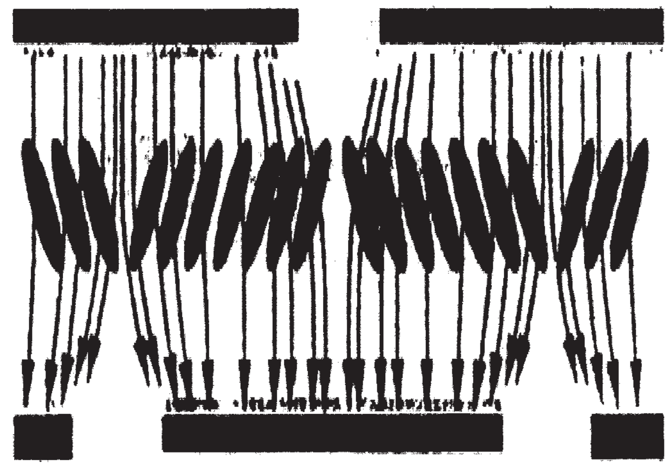


FIGURE 6 — Cross-sectional view of the PVA device with patterned ITO on both top and bottom substrates.

2.4 PVA and SE

In these devices, the LC molecules are vertically aligned under crossed polarizers with an optical compensation film. The oblique field induced by the slit-patterned ITO on the top and bottom substrate drives the LC molecules to tilt downward in several directions. The key factor in the design is how to pattern the ITOs in order for the LCs to tilt downward from an initial vertical alignment stably. Figure 6 shows the switching principle of the PVA device. Figure 7 shows one example of a real pixel in the bright state by changing the angle of the crossed polarizers. As can be seen, the shape of patterned electrode is rather complicated and the disclination lines depend on the shape of electrodes; that is, for an improper design of the pixel the width of disclination lines is not sharp. The manufacturing issue in the device is the patterning of ITO on the color filter side. The device needs fine patterning of the ITO in order to generate a well-defined oblique field. In general, the patterning of the ITO, that is in contact with the color resin or just resin makes it very difficult to obtain fine etch bias; therefore, an extra underlayer such as SiNx placed between ITO and resin is necessary. This process is not generally used in a color-filter manufacturing factory for TFT-LCDs. Although the total number of manufacturing masks for array substrate is the same as for the conventional TN device, the extra mask and extra work in the color filter side are necessary. Again, like in the MVA device, the alignment accuracy of the panel also impacts the dynamics, since an effective oblique-field controls the dynamics of the LC director. For the case of an SE device, the shape of the patterned ITOs is relatively simple, but the configuration of the LC director for real four-domain is not obtained, so the image quality is relatively lower than that of the above-mentioned VA devices. In performance, the PVA device demonstrates a high contrast ratio at normal directions due to exact vertical alignment, but shows a relatively slow gray-to-gray response time. Again, the increase in material cost is a drawback.

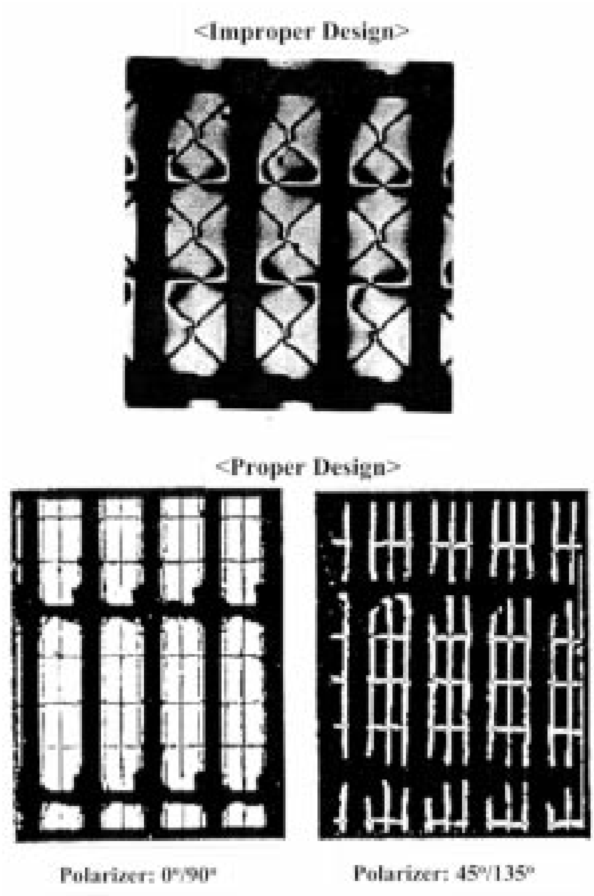


FIGURE 7 — Microscopic texture of the PVA device with improper and proper design of the patterned ITOs.

2.5 Other VA devices

Another candidate for the VA device is one with a combination of vertical alignment and in-plane switching, referred to as VA-IPS.[15] The manufacturing process of the device is

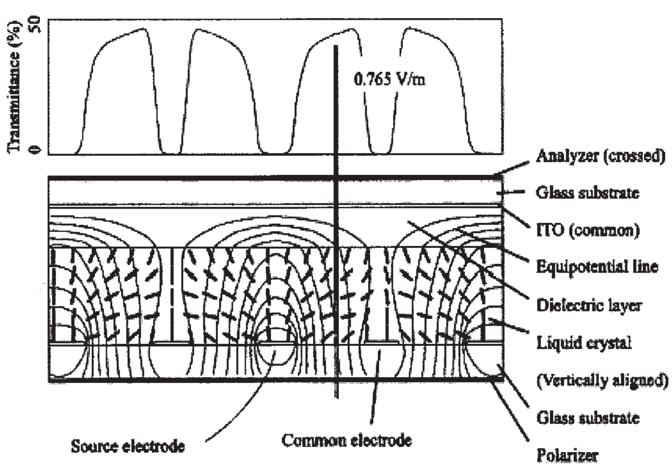


FIGURE 8 — Cross-sectional view of a new LCD mode where the LC molecules are initially vertically aligned and when a voltage is applied, are tilted downward resulting in a white state.

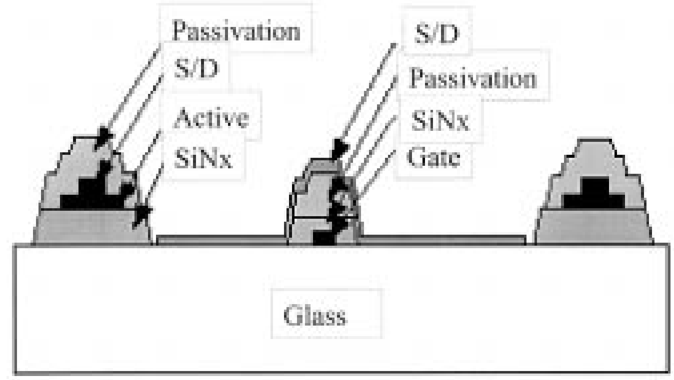


FIGURE 9 — Vertical structure of the protrusion using multilayers in the array substrate.

the simplest among the other above-mentioned devices without ITO and the need for planarization on both substrates. However, the device has a high driving voltage and lower transmittance than that for the IPS device. Recently, device upgrading for the VA-IPS has been suggested by Fujitsu.[16] In the device, an oblique field was generated by adding a dielectric layer and ITO on the top substrate, as indicated in Fig. 8. The device shows improved light transmittance and an extremely fast response time of less than 16 msec for all gray levels. In the manufacturing process, only one more mask on the color-filter side for ITO to make contact with the common electrode on the bottom substrate is required, compared to that of the TN device. The device seems superior in response time, viewing angle, and process margin, but its relatively low transmittance is still an intrinsic problem.

Other approaches to manufacture the VA device involve methods of making protrusions.[17,18] Instead of forming a protrusion with an additional process on the top substrate, it is formed by using multilayers such as gate, data, gate insulator, and passivation only on the array substrate, as shown in Fig. 9. It has an advantage in terms of using a conventional production line and process, but it is rather difficult to control the stability of the LC director, and an appreciable decrease in light transmittance is unavoidable.

3 Summary

The competitiveness of wide-viewing-angle TFT-LCDs depends on performance and cost. The performance is an intrinsic characteristic of the device, but the cost is determined by material, yield, throughput, and also on each manufacturer's process capability. The TN manufacturing process is standard and well known, allowing for high yield and competitiveness in cost. The film-compensated TN only needs to improve upon image quality in order to become highly competitive. The FFS and IPS devices need to improve yield, and the VA devices need to lower cost or improve yield to compensate for their high cost. Thus far, the film-compensated TN and IPS modes seem to use almost the same process as that of the TN modes. Other devices need more masks compared to the TN process. What is evident is that the new devices are more sensitive to the manufacturing process than the conventional TN device, whereas they exhibit better image quality with fast response time. Further, there is no single device that exhibits high transmittance, fast speed, wide viewing angle with minimized color shift as viewing direction changes, less masks, and a wide process margin. Each device has some intrinsic problems that cannot satisfy all requirements although research is continually being performed. At present, the price of TFT-LCDs are still high and their performance must be improved, comparable to those of the CRT. Therefore, improvements not only in LC devices but also in their manufacturing process must be made in order for them to be highly competitive among other flat-panel displays. Some new processes such as fabricating new LC alignment layers using diamond-like carbon film[19] and one-drop filling[20] are under evaluation at this point to reduce product cost and increase image quality. Recently, we have developed "Ultra-FFS TFT-LCD" devices that demonstrate both high performance and low cost, which we believe are strong candidates for high-competitive LCDs.[21]

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Seung Hee Lee received his B.S. degree in physics from Chonbuk National University in 1989 and Ph.D. degree from the Physics Department of Kent State University in 1994 in the area of molecular dynamics of a polymer/liquid-crystal system. In 1995, he joined the LCD division of Hyundai Electronics. Since then, he has been working on the development of liquid-crystal devices, especially wide-viewing-angle TFT-LCDs and developed the "Fringe-Field Switching (FFS)" mode. In 1997, he was awarded "Outstanding Poster Paper" at IDW. In September of 2001, he became a professor at the Department of Polymer Science and Technology at Chonbuk National University in Chonju, Korea. He has published numerous papers and has filed over 100 patents in this area.

Seung Ho Hong obtained his B.S. and M.S. degrees from the Physics Department of Korea University in 1996 and 1998, respectively. He joined the LCD division of Hyundai Electronics in 1998. He is currently working on the development of the TFT-LCD LC device, especially the optical design of the LC device using simulation, as a research engineer.

Jin Mahn Kim obtained his B.S. and M.S. degrees from the Electrical Material Science Department of Chonnam National University in 1992 and 1994, respectively. He joined Hyundai Electronics in 1995 and did research on PDPs until 1999. He then joined the LCD division in August of 1999, where he worked on the research and development of cell process for TFT-LCDs as a research engineer.

Hyang Yul Kim received his B.S. degree from the Chemical Engineering Department of Chonnam National University in 1994 and M.S. degree from the Electrical Engineering Department of Soongsil University in 2000. He joined Hyundai Electronics in 1993 where he worked on the development of passive-matrix LCDs. He is now a section leader of the Monitor division and has been working on the development of liquid-crystal material and cell processes for TFT-LCDs. He was a co-author of the "Outstanding Poster Paper Award" at IDW '97.

Jung Yeal Lee received his B.S. degree from the Electrical Engineering Department of Seoul National University in 1983. After graduating, he joined Samsung Electronics and worked on the SRAM design until 1991. While working at Samsung, he obtained his M.S. degree from the Electrical and Electronics Engineering Department of KAIST in 1987. In 1991, he joined the LCD division of Hyundai Electronics. Since then, he has been working on areas such as TFT-LCD design, process integration, and product integration. During this time, he received his Ph.D. degree in low-temperature poly-Si TFT devices from the Electrical and Electronics Engineering Department of KAIST in 1995. Currently, he is a leader of the TFT-LCD product engineering team.