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Super High Quality MVA-TFT Liquid Crystal Displays

●Yoshio Koike ●Kenji Okamoto

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This paper describes a technology for applying the vertically aligned (VA) system to Multi-domain Vertical Alignment (MVA) liquid crystals to fabricate TFT liquid crystal panels. We achieved a wide viewing angle (160° vertically and horizontally) and a rubbing-free process which contributes to a high throughput performance by using four-domain alignment. To obtain four-domain alignment, we created chevron-patterned ridges on the substrate (each ridge has two slopes). This paper also describes some ongoing developments which further improve the display characteristics of MVA-TFT liquid crystal displays and their production productivity.

1. Introduction

The market for liquid crystal (LC) monitors is growing fast as users replace their bulky CRT monitors. For high-end monitor applications, we have developed multi-domain vertical alignment (MVA) thin-film transistor (TFT) LCDs. These LCDs are based on a new vertical alignment concept. They offer a wide viewing angle, a high contrast ratio, and a short response time. In addition, the MVA technology used to make these LCDs eliminates the need for a rubbing process, which makes manufacturing simpler and the MVA-TFTs more stable.

As LCD technology advances, LCDs are replacing CRTs on many desktops, mainly because LCD monitors take up far less space than conventional CRT monitors. However, space is not the only factor to be considered when choosing a monitor. For LCDs to be practical monitors, they must also offer a sufficiently high contrast, a wide viewing angle, and a quick response time. Also, as human-machine interfaces for the expanding visual information world, they also need to be agreeable ergonomically.

To many experts, the LCD's greatest drawback has been its narrow viewing angle. Responding to this problem, researchers in the last few years have proposed several ways to widen the viewing angle. One of these is the in-plane-switching system (IPS), which substantially improves the viewing angle without additional optical compensations. However, this system does not produce satisfactory colors or response speeds.

We studied various systems to develop LCDs that would satisfy all monitor requirements. Using a vertically aligned LC system, we have succeeded in developing one of the industry's highest performing LCDs in terms of contrast ratio, viewing angle, and response time.

2. Operating principles of various LCDs

Twisted nematic (TN) LCDs, in-plane-switching (IPS) LCDs, and vertically aligned (VA) LCDs all operate under different principles (**Figure 1**). In conventional TN-LCDs, when the applied voltage is zero, the LC molecules are aligned almost in the same plane as

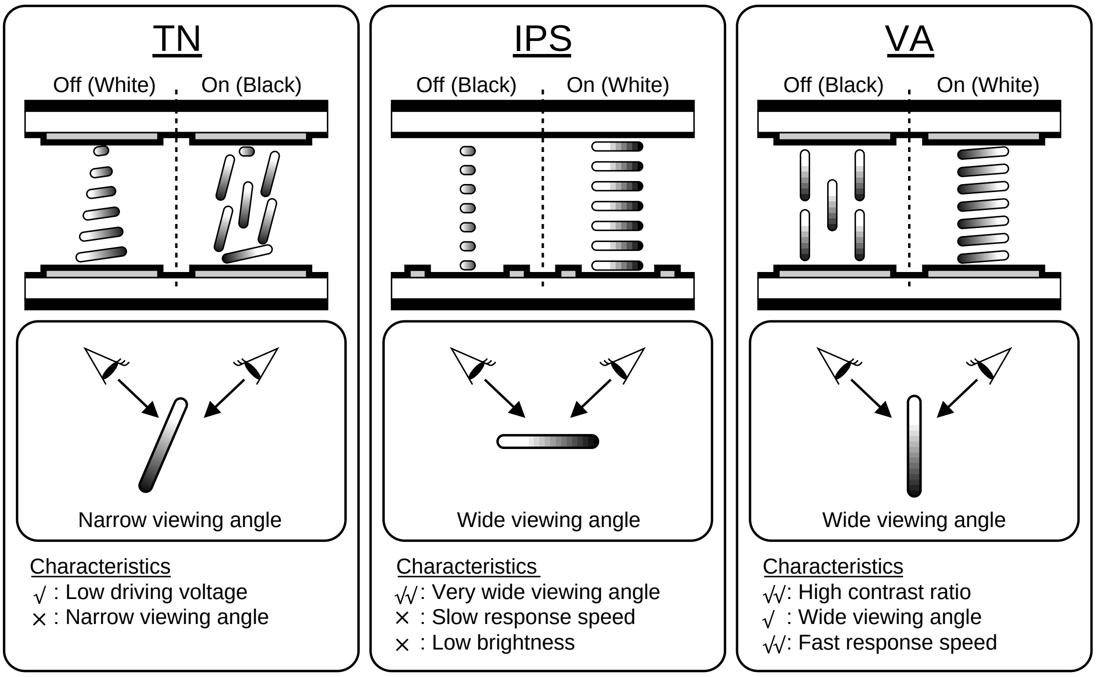


Figure 1
Comparison of liquid crystal display modes.

the front and back substrates, and there is a gradual 90-degree displacement in the horizontal orientations of the LC molecules over the distance between the substrates. Light enters the panel through the incident polarizer and passes through the LC layer, which rotates the light by 90 degrees because of the gradual change in horizontal orientations. Then, the linearly polarized and rotated light passes through a second polarizer, which is oriented at 90º to the incident one. This light produces white on the display.

When the full voltage is applied to the TN-LCDs, the twisted structure is disrupted and the alignment becomes almost perpendicular to the substrates. The polarized light entering the cell now passes through the LC layer without being rotated. Because there is no rotation, the second polarizer blocks the light, producing black on the display.

In this type of TN-LCD, even when the full voltage is applied, the LC molecules are not completely perpendicular. Therefore, the black is not perfectly black. Furthermore, when an intermediate voltage is applied, the various polar alignments of LC molecules in each cell produce different images from different viewing angles. That is, viewers looking at the display from other than directly in front do not see a clear and correct image.

In the IPS system, the LC molecules lie in the same plane as the substrates and rotate in that plane according to how much voltage is applied. This eliminates the problem of the narrow viewing angle caused by different polar components of LC alignment.

However, in the IPS, there exists some inevitable wavelength dispersion, so the transmittances are different for different colors (wavelengths) of light. This means there are some color changes over different viewing angles and applied voltages. Also, the system has a slow response because the LC molecules are rotated in the substrate plane under a rather weak field created by a pair of precisely patterned electrodes. The spacing between the patterned electrodes is generally larger than the spacing between the two substrates (which determines the response speed of conventional LCDs).

The VA system differs from both the TN and IPS systems. In the VA system, the LC molecules are aligned perpendicular to the substrates when no voltage is applied, thus producing a black image.[1),2)] When a voltage is applied, the molecules shift to a horizontal position, producing a white image. With no voltage, all the LC molecules, including those at the boundaries with the substrates, are completely perpendicular. In this state the polarized light passes through the cell without interruption from the LC molecules and is blocked by the front polarizer. Because the blockage is complete, the quality of black produced in this way is excellent and the viewer sees this black from all viewing angles. This system can achieve faster response speeds because there is no twisted structure and the LC molecules are simply switched between the vertical and horizontal alignments.

However, as with ordinary TN-LCDs, the viewing angle of the VA system is narrow for intermediate graduations. The next chapter describes this problem with the VA system and a new technology called "domain-dividing" we developed to overcome it.

3. Domain-dividing

The conventional mono-domain VA technology uniformly tilts the LC molecules to display an intermediate gray scale (**Figure 2(a)**). Because of the uniform alignment of LC molecules, the brightness changes depending on the viewing angle. When this type of cell is viewed from the front, the viewer sees only a part of the light that entered the LC cell because the birefringence effect of the tilted LC molecules is only partial for viewers from the front. If a cell in this state is observed in the direction of the tilt, the birefringence effect disappears and the area appears dark. On the other hand, if the cell is observed in the direction normal to the tilt, the birefringence effect by the LC molecules reaches the maximum, producing a high brightness.

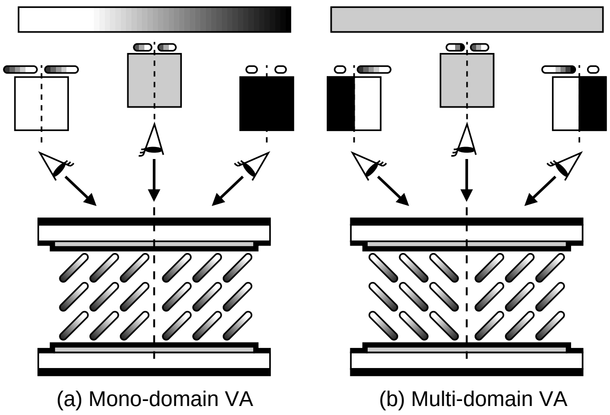


Figure 2
Mono-domain and multi-domain alignments.

To solve this problem, we use the domain-dividing technology. With this technology, the molecules on the left and right sides of the cell are arranged so that they tilt in opposite directions (**Figure 2(b)**). By combining areas of molecules oriented in one direction with areas of molecules oriented in the opposite direction, and by making the areas very small, we can make the brightness of the cells appear uniform over a wide range of viewing angles.

This domain-dividing technology, which is indispensable for widening the viewing angle, can be used for conventional TN-LCDs. For TN-LCDs, we adopted a single rubbing method[3)] which utilizes the differences in pretilt angles caused by irradiating the alignment layer with ultraviolet light. In this case, two domains will be the limit for mass production. However, simulation results have shown that at least four domains are needed to balance characteristics such as the contrast ratio, chromaticity, and brightness over different angles. Therefore, implementing four domains is a major requirement for better display performance.

4. Development of MVA technology

Seeking a way to mass produce VA-LCDs, we have developed a new LC alignment technology that does not require rubbing. The new technology involves creating ridges on the substrate to obtain an inclined or biased alignment at the ridges. When a potential difference is applied across the two substrates, the oblique electrical fields around the ridges assist the LC molecules to incline as shown in **Figure 3(a)**. This method provides a high degree of domain formation because the oblique electrical fields coincide with the initial biased LC alignments at the ridge slopes.[4] In this way, the LC molecules automatically divide into two LC alignments to create two domains with opposite viewing characteristics, thus producing cells with wide viewing angles. We call this alignment technology "automatic domain formation (ADF)." To further stabilize the LC domains, we arrange ridges on both the substrates (**Figure 3(b)**). With this technology, we can easily create any LC domain by changing the arrangement of the ridges on the substrates, especially the directions of a striped ridge pattern. For the MVA LCDs we have developed, we used four domains to maximize the performance of VA-LCDs. The ridge design we adopted for TFT-LCDs is shown in **Figure 4**. By arranging the ridges in a chevron pattern we can obtain four-domain type MVA-LCDs.[5] In this case, the angle between the absorption axis of the polarizers and the long axis of the LC molecules is 45º, where the light utilization efficiency is maximum.

5. Rubbing-free process for mass production

MVA LCDs require no rubbing treatment. Implementing a rubbing-free process has been a dream of devoted LCD engineers for a long time. This is because it is hard to precisely control the rubbing conditions so that contaminants and display unevenness (i.e., rubbing lines) are kept within acceptable levels.

Furthermore, with MVA LCDs it is possible to forecast the emergence of display unevenness merely by observing the uniformi-

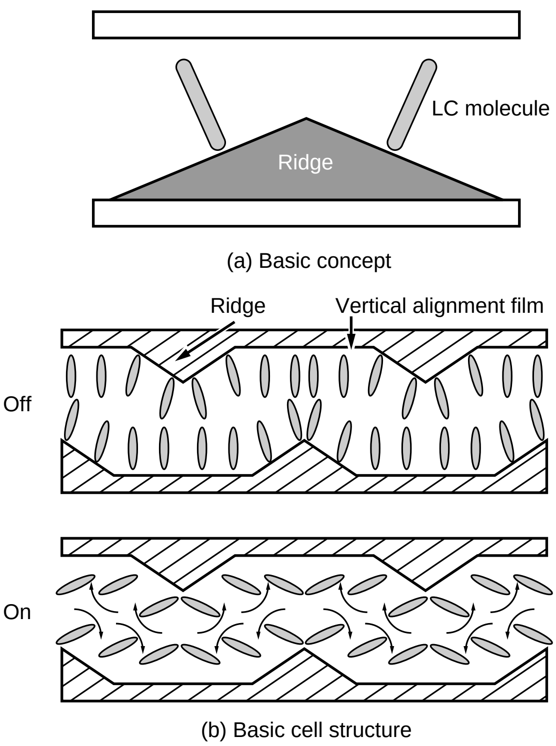


Figure 3
Operating principle of MVA-LCD.

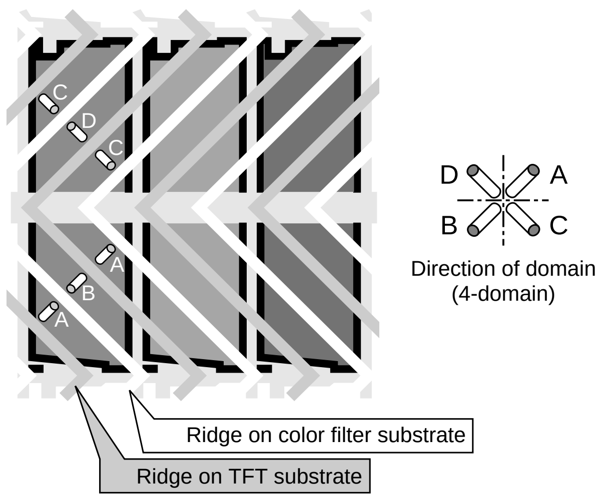


Figure 4
Ridge design.

ty of the ridges formed on the substrates. This is because, for any given material, the alignments of the LC molecules are solely determined by the shapes of the ridges. Therefore, it is now possible to detect bad substrates with improper alignments before they are glued, which is a major breakthrough for mass productions that include a rubbing stage. ADF technology, therefore, is also a major breakthrough in production technology.

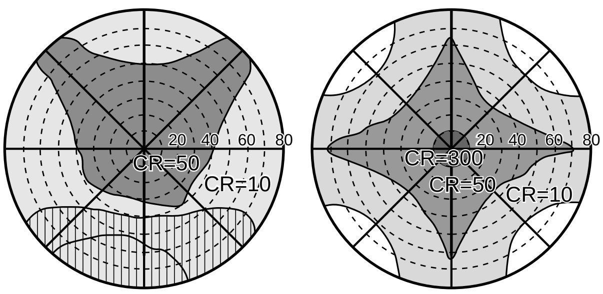
6. Characteristics of MVA LCDs

The viewing angle characteristics of four-domain MVA-LCDs are perfectly symmetrical vertically and horizontally, and the viewing angle in the vertical and horizontal directions is 160º or more (**Figure 5**). Over this vertical/horizontal 160º viewing angle, the contrast ratio is 30:1. Even over a vertical/horizontal viewing angle of 180º the contrast ratio is still 10:1. In the diagonal direction, for a contrast ratio of 10:1, the viewing angle is 120º.

Inversion of grayscale levels, which is a major problem affecting image quality, does not occur at all in these new displays. Also, the dependency of chromaticity on the viewing angle is considerably reduced, so an accurate color reproducibility equivalent to that of CRTs can be expected. Compared with the characteristics of mono-domain technologies, it is clear that a four-domain technology greatly contributes to improving the display performance.

Table 1 shows the major performance features of our first 15-inch MVA-LCD monitor, which was put on sale in 1997. The number of pixels is equivalent to that of XGA with 64 grayscales. The brightness is 200 cd/m^2 and is enough for general uses. Because MVA-LCDs are normally black they can have a higher aperture ratio than normally white LCDs. A greater substrate-to-substrate alignment error can be accepted in the liquid crystal fabrication process, and the standard contrast ratio is 300:1. The response time is as fast as 25 ms. The rise time is 15 ms, and the decay time is 10 ms or less. The 10 ms response from white to black, which is the most recognizable transition to human eyes, is particularly fast. This LCD panel is therefore suitable for reproducing moving images.

VA-LCDs have been hampered by reliability problems that include problems with burn-in and mass productivity due to display unevenness. The ADF technology we have developed solves these problems. Since the alignment layer surface need not be touched at all once it is coated, the margins for various types of contamination have been dramatically widened. The results of burn-in tests show that MVA-LCDs are on the same level as conventional, horizon-



(a) Mono-domain VA-LCD (b) 4-domain MVA-LCD

: Grayscale inversion region

Figure 5
Viewing angles of VA and MVA-LCD.

Table 1
MVA-TFT module specifications.

Display area	15-inch diagonal
Number of pixels	1024 × 768 × RGB
Number of colors	260 000
Viewing angle (CR > 10)	160° or more (no inversion)
Contrast ratio (max.)	300:1 or more
Response time	Less than 25 ms
Brightness	200 cd/m^2
Driving voltage	5 V

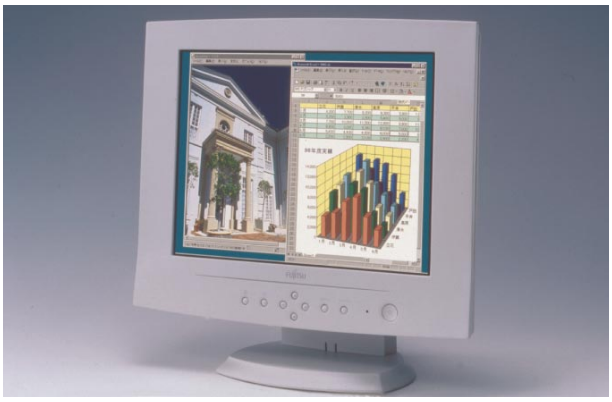


Figure 6
15-inch MVA TFT-LCD monitor (VL-1510T).

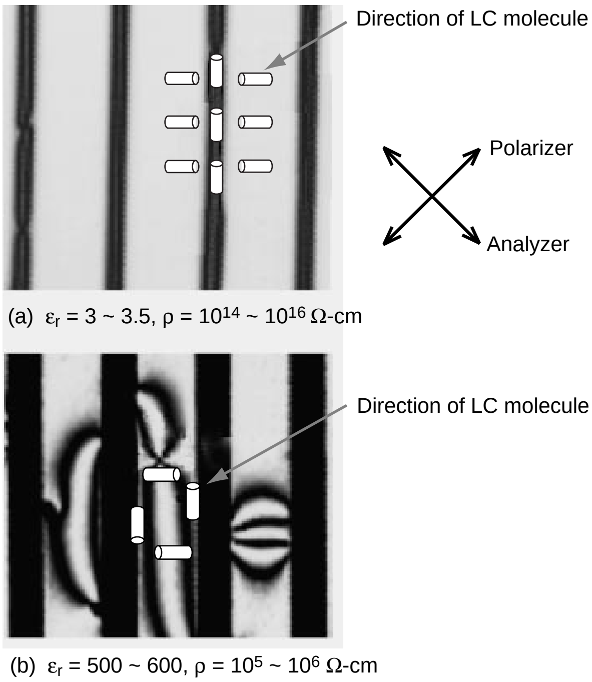


Figure 7
Effect of electrical properties on LC domains.

tally aligned TN-LCDs.

The VL-1500T liquid crystal monitor (**Figure 6**) is our first product to feature MVA technology. The display quality of this monitor from directly in front is almost as good as that of CRTs.

7. Further progress

MVA-LCDs produce a high display quality, especially in terms of the viewing angle, and can be made with a high manufacturing yield (particularly because there is no rubbing process). However, there still exist some points to be improved. One of these points is the process for forming the ridges. As mentioned above, we need to form the ridges on both substrates. Because this means we need two photolithography processes to make a panel, we tried to replace the ridges on one or both of the substrates.

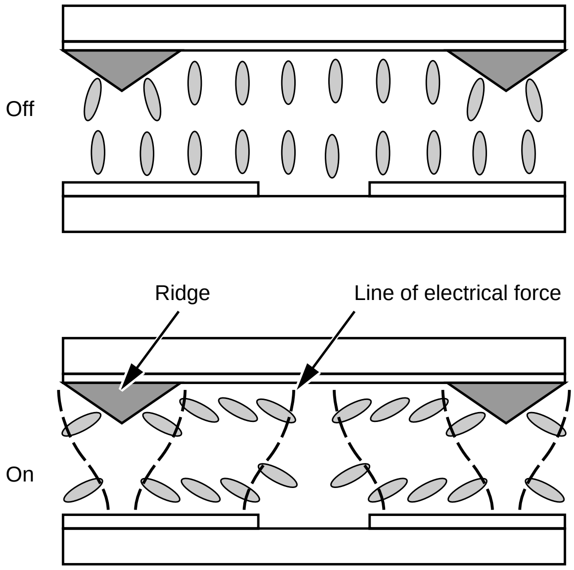


Figure 8
Structure combining a slit and ridges.

At first we studied the precise mechanism of LC domain control in MVA-LCDs and found that, in addition to the shapes of the ridges, the resistivity and dielectric constant of the ridge material also have an important effect on the LC domains (**Figure 7**). This means that the oblique electrical fields around the ridges also have an important role in LC alignment, which led us to the new panel structure shown in **Figure 8**. In this structure, the ridge on one substrate is replaced by a patterned ITO slit. Basically this concept is well known and is almost the same as that already reported by Lien et al.[6] We made slit patterns in each pixel of the TFT substrate in order to keep the same viewing angle characteristics and response time

Table 2
Recent improvements in 15-inch MVA-TFT LCDs.

	Original	Improved
Aperture ratio (%)	57.9	67.6
Transmittance (%)	3.4	4.5
Brightness (cd/m^2)	200	250
Contrast ratio (max.)	300:1	500:1
Response time (ms)	25	25
MVA process steps	2	1

as in the original MVA panel. We optimized the slit width and obtained almost the same characteristics as the previous MVA panel.

By eliminating the ridge step, no additional process is required for the TFT substrate. This significantly reduces the production cost of the MVA-TFT. In addition, the ITO slit structure has the advantage of increasing the contrast ratio of the MVA panels. Since the contrast ratio is mainly determined by the leakage light through the region of tilted LC molecules (i.e., near the sides of the ridges) when no voltage is applied, the replacement of ridges by ITO slits almost halves the leakage light. This results in a huge contrast ratio improvement of typically from 300:1 to 500:1. No change in the switching speed was observed in panels made with this modified structure.

In addition to the improvement in production processes, we also improved the transmittance of the MVA panel by redesigning the black matrix pattern and the ridge pattern. The black matrix pattern is related to the aperture ratio that is optimal for normally black MVA-LCDs, and the ridge pattern is related to a new additional pattern that can remove the disclination lines near the pixel edges. **Table 2** summarizes the improvements of our recent developments.[7] These improvements have already been incorporated in our newest MVA-TFT LCDs. We will continue to improve the performance, productivity, reliability, and other aspects of our MVA-FFT LCDs to meet the needs of the growing visual information society.

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Yoshio Koike received the B.S. and M.S. degrees in Applied Physics from Waseda University, Japan in 1979 and 1981, respectively. He joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1981, where he was engaged in research and development of electrochromic displays. Since 1983, he has been engaged in research and development of LCD technology at Fujitsu Laboratories Ltd. Atsugi, Japan.

E-mail: koike@lcd.ed.fujitsu.co.jp

Kenji Okamoto received the M.E. and Ph.D. degrees in Electrical Engineering from Tottori University, Japan in 1978 and from Osaka University, Japan in 1981, respectively. He joined Fujitsu Laboratories Ltd., Japan in 1981 and has been engaged in research and development of inorganic electroluminescent displays. Since 1988, he has been involved in LCD technology. He received the Special Recognition Award from the Society for Information Display (SID) in 1999.

E-mail: kokamoto@lcd.ed.fujitsu.co.jp