Control of reverse twist domain near a pixel edge using strong vertical electric field in the fringe-field switching liquid crystal device

Mi Sook Kim[a)]
SBU Development Center, BOE TFT LCD SBU, San 136-1, Ami-ri, Bubal-eup, Ichon, Kyungki-do 467-701, Korea and Research Center for Advanced Materials Development, School of Advanced Materials Engineering, Chonbuk National University, Chonju, Chonbuk 561-756, Korea

Seung Min Seen[b)]
Dept. of Applied Physics, Korea University, Chochiwon, Chungnam 339–700, Korea

Seung Hee Lee[c)]
Research Center for Advanced Materials Development, School of Advanced Materials Engineering, Chonbuk National University, Chonju, Chonbuk 561-756, Korea

(Received 29 August 2006; accepted 18 February 2007; published online 29 March 2007)

In the fringe-field switching (FFS) liquid crystal (LC) device, competition between two opposite forces to twist LCs exists near the pixel edge. The authors proposed an advanced FFS structure with the strong vertical field near the pixel edge which was induced between Cr black matrix (BM) and pixel electrode due to electrical connection between the Cr BM and the common electrode. The vertical field induces a tilt angle of LCs which increases with increasing field intensity. As a result, the degree of twist in the reverse direction decreases with increasing the pixel voltage, and thus voltage-dependent LC dynamics becomes very stable even at high applied voltages. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2715494]

Today, liquid crystal displays (LCDs) using a wide viewing technique have been greatly used in various applications such as mobile phones and notebook personal computers. Among several technologies, in-plane switching[1,2] (IPS) mode with wide viewing characteristics was the first one that exhibited high image quality, although it showed intrinsically low transmittance. On the other hand, the fringe-field switching (FFS) mode,[3,4] which is driven by a fringe electric field, is the representative one that showed high transmittance and wide viewing characteristics at the same time. Actually, in the FFS mode using the LC with positive dielectric anisotropy, the horizontal field direction of the active region is different from that near the edge of the pixel slit owing to the patterned pixel edge shape. Moreover, the LC directors placed at these locations differ in orientation from their neighboring directors at applied voltages, i.e., an area with reverse twist[5] are formed causing disclination lines (DLs). Since LC dynamics in this area is very unstable, especially at a high voltage, DLs easily extend into an adjacent pixel area, resulting in low transmittance and dynamic instability. Therefore, to achieve a high performance FFS device, it was necessary to control the reverse twist region via optimal design of a pixel electrode and several approaches[6–9] were reported. Nevertheless, those approaches decrease the transmittance.

To solve this problem, we suggested an advanced FFS structure with a strong vertical field at the edge of the pixel, which is generated between Cr black matrix (BM) and pixel electrode. Here, the Cr BM is connected to the common electrode on the bottom substrate so that the signal of the common voltage is applied. In this letter, we discuss how a vertical field reduces the twist angle in the opposite direction, thereby increasing transmittance and voltage-dependent dynamic stability of the LCs.

Figure 1 shows cross-sectional and top views near the edge of a pixel in the conventional FFS mode. As can be seen, the electrodes exist only on the bottom substrate. The common electrode exists in the plane form and the pixel electrode with patterned slits exists with a width w and a distance l'. With this structure, the fringe electric field having both horizontal and vertical components is generated with a bias voltage. The slit angle is θ, which is 7° in this case. The rubbing direction is given to the horizontal direction so that the LC director makes an angle of 83° with respect to the horizontal component of the fringe field. With this pixel structure, the field direction of the horizontal component in the active region is different from the direction near the edge of the pixel slit due to the patterned pixel edge shape, as shown in Fig. 1(b). For a test, the w and l' are designed to be 3 and 5 μm, respectively. The cell gap (d) is 4 μm. The thicknesses of the passivation and insulation layers are 4000 and 2000 Å, respectively. The LC with a positive dielectric anisotropy ($\Delta n=0.098$ at $\lambda=589$ nm, $\Delta\varepsilon=8.2$) is used.

In the FFS device where a uniaxial medium exists under crossed polarizers with its optic axis coincident with the po-

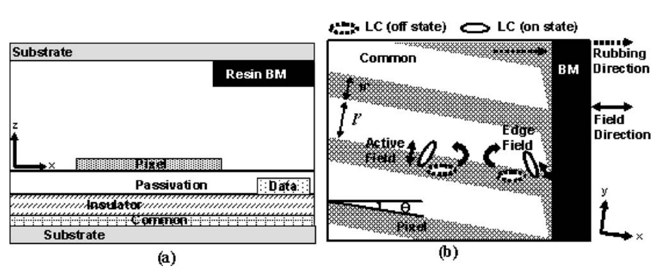

FIG. 1. Schematic cell structure near the pixel edge in the conventional FFS mode: (a) cross-sectional and (b) top views.

[a)]Electronic mail: misuk7287@boehydis.com
[b)]Electronic mail:dega@lge.com
[c)]Electronic mail: lsh1@chonbuk.ac.kr

0003-6951/2007/90(13)/133513/3/$23.00

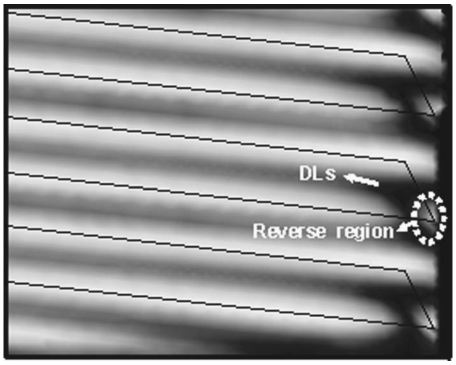

FIG. 2. Transmittance near a pixel edge of the conventional FFS structure in a white state.

larizer axis, the normalized transmission of light can be described by

$$T/T_0 = \sin^2(2\psi(V))\sin^2(\pi d\Delta n/\lambda),$$

where ψ is the angle between the polarizer and the liquid crystal director. Therefore, the FFS mode is a normally black mode and the transmission becomes maximal when the LC director is rotated by 45° by an applied voltage. Due to use of positive dielectric anisotropy, the LC orients parallel to the field direction. However, in this device, the twisting direction of voltage dependent ψ in the active area is different from that in the edge area, that is, opposite each other due to different field directions, resulting in collision between LCs. This causes generation of DLs.

First, we have performed a computer simulation to investigate voltage-dependent transmittance characteristics and DLs near the pixel edge. For the simulation, we have used the commercially available software TECHWIZ LCD (Sanayi System, Korea), where the motion of the LC director is calculated based on the Eriksen-Leslie theory and 2×2 Jones matrix[10] is applied for optical transmittance calculation.

Figure 2 shows the transmittance with DLs near the pixel edge. As already mentioned, the horizontal field direction near the pixel edge is different from that in the active region, and thus the LC directors placed at the pixel edge differ in orientation with neighboring directors, i.e., the LCs rotate in anticlockwise direction in the active region while the LCs rotate clockwise in the edge region. Because of the existence of a reverse twist, the LC molecules existing at the boundary cannot rotate in either direction, and thus LC remains at the original state, giving rise to dark DLs. Moreover, the DLs extend into the active area at a high applied voltage, and thus the transmittance in the panel is rapidly

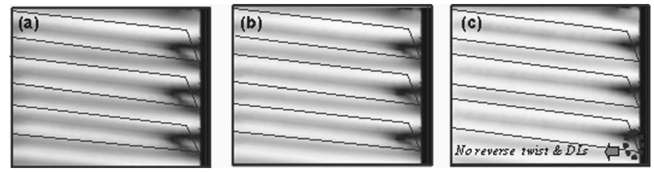

FIG. 3. Transmittance change near pixel edges with increasing the vertical field in the advanced structure when the voltage differences between the pixel and common electrodes are (a) 3.5 V, (b) 4.5 V, and (c) 5.5 V.

decreased. Therefore, it is necessary to eliminate the reverse twist region to achieve good electro-optic properties of the FFS mode. This kind of the reverse twist was observed in the IPS mode;[11] however, the solution in the IPS mode cannot be applied to the FFS mode due to difference in electrode structures.

To solve the problem, we proposed the advanced FFS structure with strong vertical field near the pixel edge. Here, the vertical field is generated between Cr BM and the pixel electrode by electrically connecting Cr BM to the common electrode on the bottom substrate.

Figure 3 shows how the transmittance changes with increasing the applied voltage to the pixel electrode from 3.5 to 5.5 V with respect to the common electrode 0 V at the advanced structure. More clearly indicated in Fig. 3, even at the voltage difference of 3.5 V, is that the level of darkness in DLs becomes weak, i.e., more light is transmitted in the advanced structure than in the conventional one. Besides, the degree of DLs in terms of darkness and intrusion into the active region reduces as the voltage difference between the pixel and common electrode increases. From these, we can understand that as the vertical field increases, the reverse twist near the right bottom corner of the pixel edge disappears, giving rise to improved transmittance.

To confirm the calculated results, we fabricated unit test cells. Figure 4 shows an optical microscopy image of the cells with two different structures when operating voltage is applied to the each cell. As clearly indicated, the DLs in the cell with strong vertical electric field in Fig. 4(a) are greatly reduced compared with the one without vertical electric field in Fig. 4(b) (compare DLs inside the dotted square box). In addition, DLs near the pixel edge barely extend into the active region in the advanced structure.

To understand vertical field effects on reverse twist, the field intensities of the vertical (E_z) and horizontal (E_y) electric fields near the pixel edge which cause reverse twist are calculated at three different voltages, as shown in Fig. 5. At this point, the field intensity of E_z is stronger than that of E_y

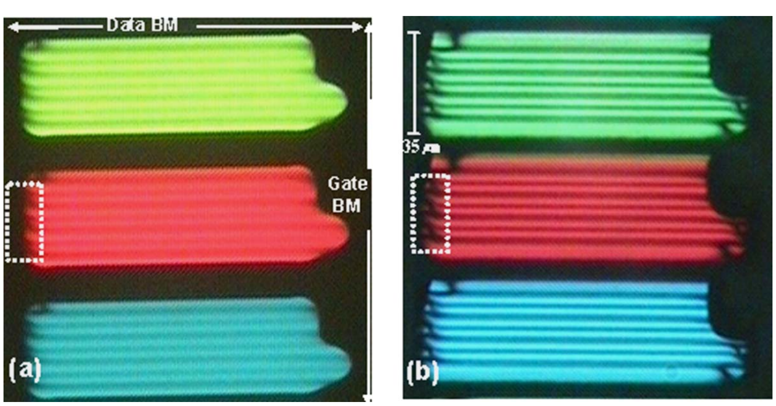

FIG. 4. (Color online) Optical microphotographs of the test cells (a) with and (b) without the vertical field.

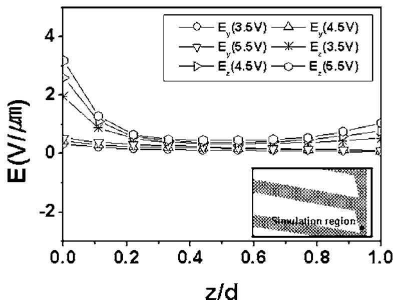

FIG. 5. Distribution of the horizontal and vertical electric fields near the reverse twist region at different voltages in the advanced structure.

at each vertical distance, which indicates that the LCs near this region is more influenced by E_z than E_y, indicating that the LCs experience tilt deformation rather than twist one. In addition, the strong field intensity of E_y near the bottom substrate decreases with increasing vertical distance.

Finally, we calculated the orientation of the LC director, in a reverse twist region where the field competition exists, to analyze an increase in transmittance. Figures 6(a) and 6(b) show the twist and tilt angles of the LC along the vertical axis while increasing applied pixel voltage from 3.5 to 5.5 V. As can be seen in Fig. 6(a), the LCs are reversely twisted, i.e., negative twist angle when the top electrode does not exist and the tilt angle is less than about 5° along vertical distances. However, as the Cr BM on the top substrate exists and the voltage difference between the pixel and common electrodes is induced, the tilt angle in this region is generated and it becomes larger and larger with increasing voltage. Consequently, the torque to rotate the LCs in a reverse direction becomes weak except just near the bottom substrate ($\sim z/d=0.1$) where a dielectric torque between strong E_y and low tilt LC causes reverse twist, and thus most LC layers are twisted in anticlockwise direction, resulting in disappearance of DLs. Especially, all LCs rotate anticlockwise at the high voltage of 5.5 V, indicating that the voltage-dependent LC dynamics becomes stable with increasing voltage at the edge of the pixel.

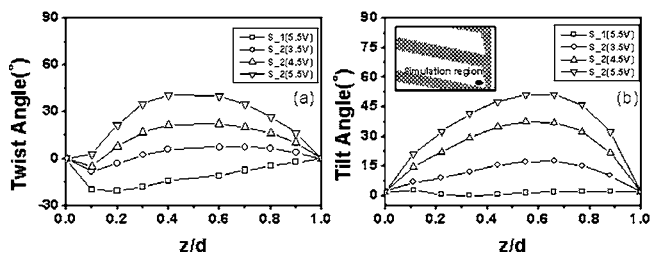

FIG. 6. Voltage-dependent (a) twist and (b) tilt angles of LCs at two different structures. Here S_1 and S_2 indicate conventional and advanced structures, respectively.

In summary, we proposed an advanced FFS structure having strong vertical field near the pixel edge. This structure minimizes DLs near the pixel edge, thereby increasing transmittance. Further, the device has the advantage of keeping LC dynamics stable even at high applied voltage. We expect that this pixel structure would accelerate the FFS-LCD applications for high resolution and pen-based tablet PC.

[1]M. Oh-E and K. Kondo, Appl. Phys. Lett. **67**, 3895 (1995).
[2]H. Y. Kim, I. S. Song, and S. H. Lee, Trans. Electr. Electron. Mater. **4**, 24 (2003).
[3]S. H. Lee, S. L. Lee, and H. Y. Kim, Appl. Phys. Lett. **73**, 2881 (1998).
[4]I. H. Yu, I. S. Song, J. Y. Lee, and S. H. Lee, J. Phys. D **39**, 2367 (2006).
[5]S. H. Hong, S.-H. Nam, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **42**, 2752 (2003).
[6]M. S. Kim, Y. H. Jung, S. M. Seen, H. Y. Kim, S. Y. Kim, Y. J. Lim, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **44**, 3121 (2005).
[7]M. S. Kim, S. M. Seen, Y. H. Jung, H. Y. Kim, S. Y. Kim, Y. J. Lim, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **44**, 6698 (2005).
[8]M. S. Kim, S. M. Seen, Y. H. Jung, H. Y. Kim, S. Y. Kim, K. H. Lee, Y. J. Lim, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **44**, 8802 (2005).
[9]M. S. Kim, S. M. Seen, Y. H. Jung, H. Y. Kim, S. Y. Kim, Y. J. Lim, and S. H. Lee, Jpn. J. Appl. Phys., Part 1 **45**, 883 (2006).
[10]A. Lien, Appl. Phys. Lett. **57**, 2767 (1990).
[11]T. Suzuki, S. Nishida, M. Suzuki, and S. Kaneko, J. Appl. Phys. **89**, 1 (2001).