Axis-symmetric Alignment Achieved by using a Mortar-shaped Pixel Structure for Fast Switching Twisted-vertically aligned-mode Reflective LCDs

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Abstract We have developed a fast switching twisted-vertically aligned (TVA)-mode reflective liquid crystal display (LCD) using a mortar-shaped pixel structure. We realized an axially symmetric pretilt angle in each pixel using the mortar-shaped pixel structure fabricated using UV pattern exposure. We experimentally confirmed that the axis-symmetric alignment from the mortar-shaped structure controls the start point of the alignment change in the voltage-on state over the entire surface of the pixel region, and is effective in improving the response speed of the TVA-mode LCD.

Keywords: Liquid crystal display, Reflective LCD, Twisted vertically aligned mode, Mortar-shaped pixel structure, Fast switching speed, High reflectivity, Wide viewing angle.

1. Introduction

Reflective liquid crystal displays (LCDs) 1)-4) have excellent visibility in bright environments and low power consumption, and therefore it has long been anticipated a realization of high-quality reflective LCDs and its application to a wide range of fields including large-screen digital signage.

Digital signage requires a high contrast ratio, a wide viewing angle range, high reflectivity, and a wide color gamut. However, it is difficult to satisfy these requirements with the conventional display modes of reflective LCDs, such as vertically aligned (VA) mode 5)-6) and mixed-mode twisted nematic (MTN) 7)-9). For example, in VA-mode LCDs, the white state becomes yellowish because of the wavelength dependence of the reflectance, while MTN-mode LCDs have a low contrast ratio and a narrow viewing angle range because of the twist alignment in the voltage-off state. Therefore, the development of a novel LCD mode for reflective LCDs that can solve these issues is an important challenge in realizing high quality, low power digital signage.

To overcome these problems, we have focused on the twisted-vertically aligned (TVA)-mode as shown in Fig. 1 10)-15).

In TVA-mode LCDs, LC molecules are vertically aligned in the voltage-off state, while the twisted alignment is obtained in the voltage-on state by adding a chiral dopant to the negative LCs. This feature enables a high contrast ratio, wide viewing angle, and high reflectivity due to the achromatic white state as shown in Fig. 2. For this reason, the TVA-mode is a promising display mode candidate for high-quality reflective LCDs.
In our previous works, we clarified that conventional TVA-mode LCDs have a slow switching speed in on-switching because LC alignment is controlled solely by the propagation of the elastic force from the pixel edge by the fringe electric field as shown in Fig. 3\(^{16,17}\). To solve this problem, we have proposed TVA-mode LCDs using a mortar-shaped pixel structure on the substrate surface\(^ {18}\).

Figure 4 shows the pattern diagram of the mortar-shaped surface structure. With this structure, we theoretically confirmed that it is possible to realize an axially symmetric pretilt angle on the TFT-substrate and improve the response time of TVA-mode LCDs.

In this paper, we fabricated TVA-mode LCDs with a mortar-shaped structure and investigated the fabrication process of the mortar-shaped pixel structure through pattern-UV exposure onto UV curable monomer materials, and experimentally evaluated the effect of pixel surface structure on the LC alignment and response characteristics of the TVA-mode LCDs.

2. Fabrication of mortar-shaped structure

We fabricated the mortar-shaped structure through pattern-UV exposure onto UV curable monomer materials\(^{19,20}\). Figure 5 shows a schematic of the mechanism of surface deformation. Due to the contraction caused by the difference in UV intensity between the exposed and non-exposed areas, the monomers move into the exposed region for polymerization and we can achieve concave structures on the substrate surface.

We spin-coated a UV-curable resin (NOA60; Norland Products) and irradiated the resin layer with collimated UV light (JATEC Co., Ltd.) through a photomask. The diameter of the masked area was 20 µm and the pitch was 40 µm as shown in Fig. 6\(^ {21}\). The wavelength of the UV light was 365 nm and the UV irradiation energy was 30 mW/cm\(^2\). The proximity gap between the resin layer and the photomask was 100 µm. After the first exposure, the entire surface of the resin was exposed to 20 J/cm\(^2\) integrated UV light for curing.

We fabricated the mortar-shaped structure by changing the amount of integrated UV light and measured the surface structure using confocal laser microscopy (VK-9710; Keyence). Figs. 7 and 8 respectively show the three-dimensional observation image and cross-sectional profile of the fabricated mortar-shaped structure. An uneven structure appeared at intervals of 40 µm when the amount of integrated UV light was over 2.0 J/cm\(^2\), and the depth of the structure increased with an increase in the amount of integrated UV light.

Figure 9 shows the relationship between the depth of the mortar-shaped structure and the amount of integrated UV light. The increase in the depth of the structure was greatest with between 2.5 and 3.0 J/cm\(^2\) integrated UV light, and the depth became saturated over 3.0 J/cm\(^2\). We found that the depth of the structure varied widely between 2.5 and 3.0 J/cm\(^2\), and it was difficult to form a mortar-shaped structure with a uniform depth at this UV intensity. As a result, we clarified that we can achieve a mortar-shaped structure with uniform depth by irradiating the UV-curable resin with UV light at an integrated intensity of over 3.0 J/cm\(^2\).
We coated the alignment layer on the mortar-shaped structure and evaluated the shape of the structure. Figure 10 presents the measurement result of the cross-sectional profile before and after alignment layer coating. The structure depth was 0.83 and 0.48 µm before and after alignment layer coating, respectively. From these results, we confirmed that the mortar-shaped structure remained after the alignment layer coating.

3. Evaluation of LC alignment by the mortar-shaped structure

We fabricated a TVA-mode LC cell with the mortar-shaped structure and experimentally evaluated the LC alignment caused by this structure.

3-1. Fabrication of TVA-mode LCD with mortar-shaped structure

The fabrication procedure for the TVA-mode LCD with the mortar-shaped structure is shown in Fig. 11. First, we fabricated the mortar-shaped structure on the glass substrate with an indium tin oxide (ITO) electrode and coated the vertical alignment film (SE-4811; Nissan Chemical Industries). The depth of the mortar-shaped structure after the alignment layer coating was 0.5 µm.

Then, we fabricated an empty cell using bead spacers (diameter: 2.5 µm), and a mixture of LC material (MLC-2038; Merck) and chiral dopant (S-811; LCC) was injected into the cell via capillarity action. The concentration of the chiral dopant was 0.67w%.

3-2. Evaluation of LC alignment by the mortar-shaped structure

Figure 12 shows the observation result of LC alignment under a polarizing microscope (BX-50; Olympus Co., Ltd.) in the voltage-off and voltage-on states. To simplify the measurements, we used a
transmission-type optical system under crossed-Nicol polarizers. From these results, the LC alignment switched with applied voltage, and the windmill pattern that is unique to continuum-domain VA-mode LCDs was observed at 40 µm intervals in the voltage-on state. These results indicate that the LC alignment is vertical to the surface of the mortar-shaped structure and that we successfully achieved axially symmetric LC alignment in TVA-mode LCDs by using the mortar-shaped structure.

4. Evaluation of switching characteristics of TVA-mode LCD with mortar-shaped structure

We fabricated reflective-type TVA-mode LCDs with a square-shaped pixel electrode and evaluated their response characteristics to experimentally confirm the effect of the mortar-shaped structure on the response properties of TVA-mode LCDs. We fabricated the pixel electrode using the photolithography technique. The fabrication procedure is as follows. Figure 13 shows the photomask pattern for the pixel electrode; the pitch of the pixel electrode was 40 µm.

We spin-coated a photoresist (S-1818G; Dow Electronic Materials) on the glass substrate with the ITO electrode and baked it at 120 °C for 1 minute. Next, we irradiated the sample with UV light through photomasks and cured the photoresist. The center wavelength of the UV light was 435.8 nm, and the integrated amount of UV light was 160 mJ/cm². We then removed the uncured photoresist using developer (Microposit MF-319 Developer; Dow Electronic Materials); finally, we etched the ITO electrode with hydrochloric acid and removed the photoresist using acetone. Figure 14 shows the measurement result of the pattern of the fabricated ITO pixel electrode.

5. Evaluation of response characteristics of TVA-mode LCD

We fabricated a reflective-type TVA-mode LCD using an aluminum mirror reflector and a circular polarizer and evaluated the response characteristics. The cell gap was 2.85 µm for the conventional TVA-mode and 2.83 µm for TVA-mode with the mortar-shaped structure. Figure 15 shows the measurement result of the response characteristics of conventional, and our, TVA-mode LCDs using a vertical illumination polarizing microscope (BX-50; Olympus Co., Ltd.) and a high-speed sCMOS camera (Zyla; Andor). The applied voltage was 4.0 volts for conventional TVA-mode and 9.0 volts for TVA-mode with the mortar-shaped structure. These values were determined to achieve maximum reflectance for each device. The increase in applied voltage for our TVA-mode LCD is due to the voltage drop through the resin layer. In the conventional TVA-mode, the alignment change propagated from the edge to the center of the pixel via the fringe electric field, while the alignment change occurred across the entire pixel due to the axially symmetric pretilt angle from the mortar-shaped structure. Figure 16 shows the response property of the average reflectance of the TVA-mode LCDs. The response time of the conventional TVA-mode LCD was 21.25 ms and that of our TVA-mode LCD was 15.51 ms.

As a result, we experimentally confirmed that the axisymmetric alignment from the mortar-shaped structure controlled the start point of the alignment.
change in the voltage-on state over the entire surface of the pixel region, and is effective in improving the response speed of the TVA-mode LCD.

Finally, we proposed an alternative pixel structure to improve the switching speed and contrast ratio of TVA-mode LCDs. The cell thickness of TVA-mode LCD using mortar-shaped pixel structure is not uniform and it degrades the contrast ratio of reflective LCDs. The axisymmetric alignment can be obtained by controlling the distribution of electric field instead of the pretilt angle. Therefore, we proposed the slanted pixel electrode structure as shown in Fig. 17. Figure 17 shows the calculation result of the 2D distribution of the electric field and the LC director of TVA-mode LCDs using the mortar-shaped structure and the slanted electrode structure. We used simulation software (LCD MASTER 2D, Shintech Corp.) which is based on a finite-element algorithm. The liquid crystal was MLC-2038 ($n_e = 1.593260$, $n_o = 1.488640$ at $\lambda = 550$ nm and $\epsilon_1 = 4.0$, $\epsilon_2 = 9.0$ and $K_{11} = 13.8$, $K_{22} = 10.0$, $K_{33} = 18.1$, Merck). The thickness of the LC layer and the mortar–shaped structure were 2.7 µm and 0.3 µm, respectively. The dielectric constant of the mortar-shaped structure was 4.67. The applied voltage was 4.0 V. From these results, we confirmed that the LC director in the TVA-mode LCD using the slanted electrode structure tilted toward the center of the pixel as well as the mortar-shaped structure. Figures 18 and 19 respectively show the comparison of the calculation result of the switching characteristics of TVA-mode LCDs between with mortar-shaped structure and with slanted electrode structure. The distribution of reflectance in the pixel and the response time of these two TVA-mode LCDs was almost identical, therefore we confirmed that the slanted electrode pixel structure can improve the response time and contrast ratio of TVA-mode LCD with a uniform cell gap.
6. Conclusions

We have developed a fast switching twisted VA-mode reflective LCD using a mortar-shaped pixel structure. We fabricated the mortar-shaped structure using UV pattern exposure and demonstrated that the mortar-shaped surface structure achieved axially-symmetric alignment in the voltage on-state. We experimentally confirmed that the conventional TVA-mode had a slow response speed because of the propagation of the alignment change by the fringe electric field, while our TVA-mode controlled the start point of the alignment change over the entire surface of the pixel region and achieved a fast switching speed due to the axially symmetric pretilt angle from the mortar-shaped structure. Our TVA-mode reflective LCD has advantages of high reflectivity and a wide viewing angle because of the axially symmetric alignment and therefore is a promising display mode candidate for high-quality reflective LCDs for large digital signage applications.

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