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Microcell Liquid Crystal Film for High-Contrast Flexible Display Applications

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We have successfully fabricated high-contrast microcell liquid crystal displays (LCDs) using microstructure replication technology in thin plastic film substrates. These novel flexible LCDs comprise microcell replication, alignment treatments, and cell assembly. The cell gap of such flexible LCDs was maintained well by cross-type spacers formed by photolithography, despite bending: moreover, the deviation in cell gap under various bending states was less than 0.1 µm. The structure, fabrication technique, and basic display characteristics of the flexible LCD are also described. Finally, this device shows high mechanical stability against external bending, a high contrast ratio of 500 : 1, and an acceptable response time. Compared with photopolymerisation-induced phase separation, the micro-cell LCD has a higher contrast ratio, a more reliable fabrication process, and a strong potential as a high-performance flexible LCD. [DOI: 10.1143/JJAP.45.7761]

KEYWORDS: flexible display, liquid crystal, micro-cell, plastic LCD

1. Introduction

Nowadays, the applications of portable products are gaining increasing attention. Relevant technologies aim at the development of a flat-panel display with a lighter weight, thinner size, impact resistance and low power consumption. Plastic displays offer advantages such as low weight, robustness (they are less brittle than glass) and most importantly: flexibility and thinness. Therefore, the research trend of flat-panel displays has been a gradual switch from using a conventional glass substrate to a plastic substrate.[1–3] Various display technologies such as: electrophoresis display (EPD), organic light-emitting display (OLED) and flexible LCDs fabricated by the roll-to-roll process are burgeoning. In recent years, LC devices using plastic film substrates have drawn considerable attraction in electronic applications such as smart cards, personal digital assistant (PDA), and head-mounted displays mainly owing to their thinner packaging, flexibility, and low manufacturing cost. It is necessary to overcome the problems of the physical and chemical properties of plastic substrates differing greatly from the properties of glass substrates. Therefore, the production of plastic LCDs has required the development of novel technologies and materials. Among the LC technologies, the polymer matrix LCD fabricated by the photopolymerisation-induced phase separation of an LC/polymer composite has attracted considerable attention.[4–8] However, the phase-separation process has several drawbacks such as a small process window, sensitivity to the alignment layer, and polymer residuals in the unexposed region after the photoprocess. We have also spent considerable effort in developing flexible LCD[9,10] technologies to overcome the above problems.

In this paper, we propose the novel concept of a flexible microcell LCD film that possesses a high contrast ratio, an acceptable response time, and can be fabricated through a reliable process. Compared with the fabrication of conventional LC/polymer phase separation LCDs, our method is an easier process, and has a wider alignment material selection, and a larger process window. Our devices show not only high mechanical stability, using cross-type spacers fabricated by photolithography to maintain the cell gap of test cells, but also excellent optical behavior compared with those fabricated in a glass substrate. Furthermore, the contrast ratio of the flexible microcell LCD increases when the pitch of the cross-type spacers is reduced, whereas the response time increased with increasing spacer density. The microcell technology is also compatible with the roll-to-roll fabrication process; thus, it is extremely cost-effective for the mass production of high-performance flexible LCDs.

2. Experimental Procedure

The schematic structure of our flexible microcell LCD film is shown in Fig. 1(a). The substrates were made from 200-µm-thick films of poly(ether sulfone) (PES) and cleaned using alcohol. The LC layer with micro-cell structure was sandwiched between two plastic film-like substrates, onto which transparent indium–tin-oxide (ITO) electrodes had been coated, and polyimide alignment layers 80 nm thick were printed by a conventional method after forming the microcell. Crossed ultrathin polarizers covered the exterior sides of the plastic substrates. The total thickness of the micro-cell LCD film was about 680 µm.

To keep the cell gap constant, a photolithography/etching process with good repeatability was used to produce a high-quality microstructure. Therefore, the microstructure was protected from all external forces or mechanical shocks that might be applied to the composite film during bending. First, a 6-µm-thick layer of positive photo resist (PC4003, JSR) was formed by spin coating onto the substrate. Using a g-line stepper, specially designed cross-like structures were patterned on the substrate. Then, the cross-like photospacers were baked at 180 °C, which is lower than the T_g temperature, 220 °C, of the PES substrate. Therefore, the baking process did not give rise to bending in the flexible substrate. Figure 1(b) shows the three-dimensional atomic force microscopy image of the open matrix structure of 100 µm pitch on the plastic substrate. The width and height of the spacer are 10 and 5 µm, respectively. To study the electrooptical characteristics of the flexible LCD as a function of photo-

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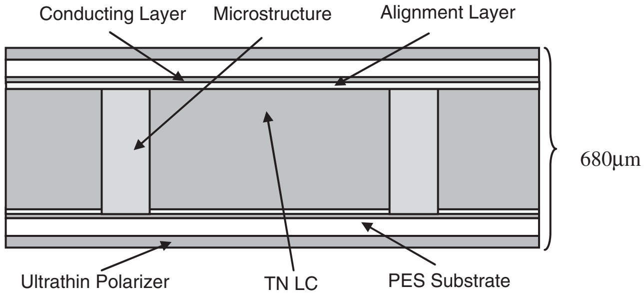
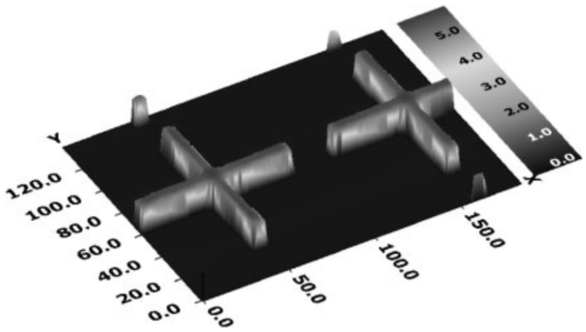
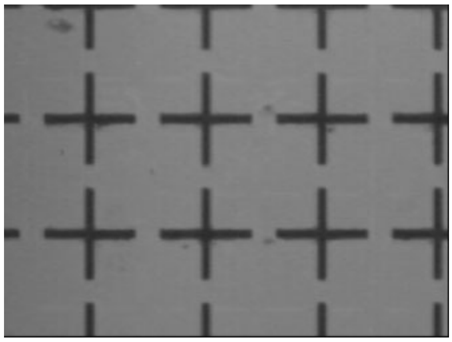


(a)

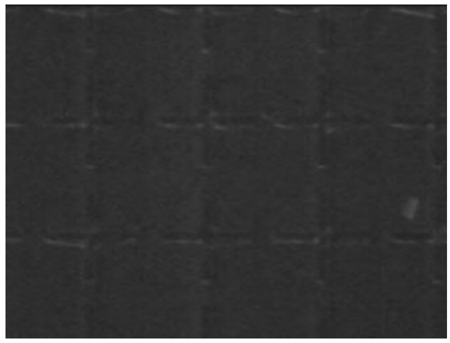


(b)

Fig. 1. (a) Cross-sectional view of flexible micro-cell LCD film. (b) Three-dimensional image of cross matrix photospacer.



(a)



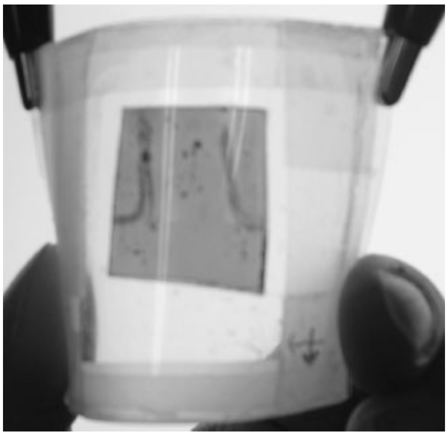
(b)

Fig. 2. (a) Bright state of TN microcell LCD at 0 V and (b) dark state driven at 5 V measured by polarizing microscope.

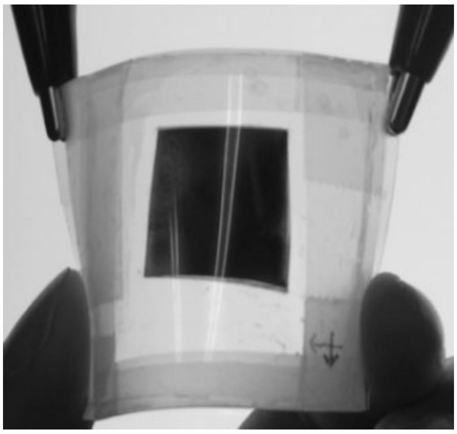
spacer density, the distance between two spacers varies from 100 to 500 μm, and the corresponding width of the spacer is a 10th of the distance between spacers, but the height of the spacer is kept constant, i.e., 5 μm. The cross-shaped open spacers were used in the microcell arrays because of their strong rigidity and ease of fabrication in the LC-filling process. The optical performance of the newly designed panel is notably maintained under bending. Thereupon, the alignment layers were printed on substrates followed by rubbing to achieve a homogeneous or homeotropic LC alignment. The rubbing alignment techniques commonly used in LCD fabrication are adopted to control the orientation of the LC molecules. This printing method enables the large-scale fabrication of flexible plastic substrates. After the lamination process, two types of test panels were fabricated: a vertically aligned (VA) panel and a twist nematic (TN) panel for electrooptical measurements. Two types of aligned material, polyimide (PI), and injected LC were used during the process: homogeneously aligned PI (SE7492, Nissan Chemical) and positive-type LC (MJ01744, Merck), for the TN-mode test panel, homeotropically aligned PI (AL60101, JSR) and negative-type LC (MLC6882, Merck), for the VA-mode test panel. Finally, two ultrathin polarizers were laminated on the upper and lower plastic substrates to complete the test panel.

3. Results and Discussion

The electrooptic performance of the microcell LCD between two crossed polarizers under various applied voltages was examined. Figures 2(a) and 2(b) show the microscopic textures of the TN-mode microcell LCD film, in which the pitch of the spacers is 100 μm, at 0 and 5 V, respectively, under a polarizing microscope. When the driving voltage is zero, the TN sample is in normally-white mode without any disclination lines in the neighborhood of the spacers. The pixels with uniformly aligned LCs with a driving voltage of 5 V show a good dark state with no more than a slight light leakage. To test mechanical stability in plastic LCDs, we compared the white and dark states of the TN test cell after external bending. Figure 3 shows that a $2 \times 3\,\mathrm{cm}^2$ device containing homogeneously aligned LC was sandwiched between two crossed polarizers and a voltage was applied between the ITO electrodes. Such a microcell LCD can be easily bent because of the thickness of 680 μm. The high quality of the images for both dark and white states was maintained while the cell was bent because the thickness of the LC layer remained constant, implying that the microstructures are robust and can sustain the cell gap well. To further prove the stability of the cell gap, the measurement of the cell gap under the bending was performed. The radius of bending curvature for the LCD film with cross-type spacers of 500 μm pitch was varied from 125 to 25 mm with a step of 25 mm, and an average cell gap of 5.97 μm with a deviation of merely 0.11 μm was obtained. The deviation was 0.09 μm when the bending direction was 45° with respect to spacers with the same pitch. Therefore, the bending tolerance is independent of the bending direction and the flexible LC cells can maintain their gaps when using such spacers. However, in Fig. 3(b), a slight light leakage occurs at the left- and right-hand edges of the device, because the viewing angle is too wide at both edges. If the viewing angle is defined as the angle with a contrast ratio equal to 10, then the horizontal and vertical viewing angles of our sample are about 62 and 78°, respectively,

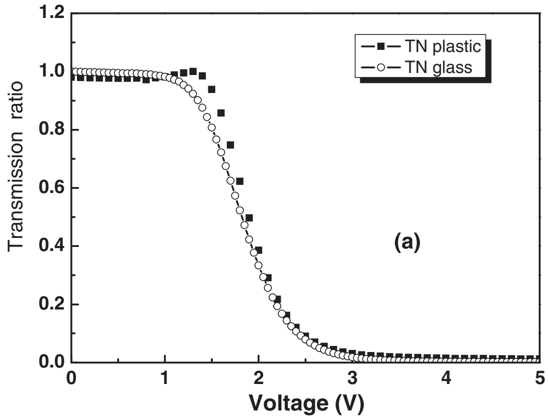


(a)



(b)

Fig. 3. Bent microcell LC device driven by voltages (a) 0 V and (b) 5 V applied to ITO electrodes.



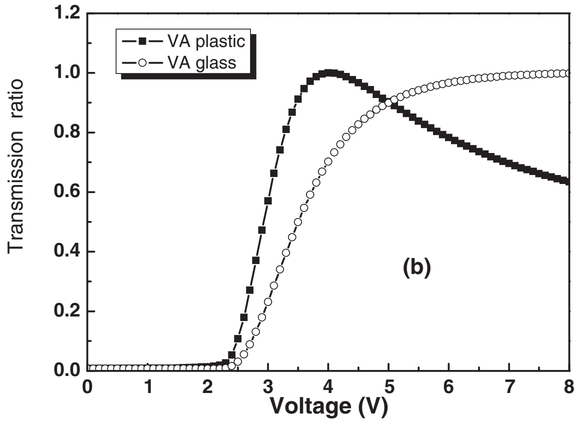


Fig. 4. Transmission versus applied voltage curves for (a) TN micro-cell LC sandwiched between plastic substrates (solid squares) and glass substrates (open circles), (b) VA microcell LC sandwiched between plastic substrates (solid squares) and glass substrates (open circles).

measured by EZContrast 160R (Eldim). Therefore, the bending angle exceeds the viewing angle resulting in light leakage from the edges of the test cell in the dark state. In addition, because the viewing angle is wider for the VA test cell, contrast reversal does not occur at the left- and right-hand edges of the devices, which are viewed in a similar way to that of the TN test cell. The horizontal and vertical viewing angles are measured to be about 60 and 58°, respectively, for the flexible VA test cell.

The flexible TN- and VA-mode devices fabricated on thin plastic substrates can be used to construct exceptionally lightweight display panels of 0.083 g/cm^2, compared with those of 0.376 g/cm^2 for panels formed by 0.7-mm-thick glass substrates. Both TN- and VA-mode flexible LCDs are extremely applicable to various electronic paper applications, such as E-book, for which a light weight is a very important issue. Furthermore, the uniform cell gap is very critical in flexible LCDs. Even when the device is cut, the ITO electrodes are not short-circuited because the cross-like photospacers maintain the cell gap between the flexible substrates; therefore, the rest of the device still functions normally. The cross-like photospacers are now developed as part of the usual LCD process. Moreover, the microcell structures can also be fabricated by other replication technologies such as embossing and UV photopolymer replication. Both techniques are currently being developed for potential mass production.

The transmission versus applied voltage (*V–T*) curves of TN and VA test cells of the same cell structure and fabrication process for both flexible and glass-substrate devices with a photospacer pitch of 100 μm, were measured using an Otsuka LCD5100 system, as shown in Fig. 4. Figure 4(a) shows the *V–T* curves of TN test cells, whose LCs are homogeneously aligned and sandwiched between two plastic substrates (solid squares) or glass substrates (open circles). The transmission characteristics are very similar for the two devices fabricated with plastic and glass substrates. The threshold voltage of the device is about 1.6 V, whereas the saturated voltage is about 5 V for both devices. In addition, the lowest dark level of this device is achieved at 10 V and provided a good maximum contrast ratio of 500 : 1, measured by the Otsuka LCD5100 system, as shown in Fig. 5. A wide-band light source is used to irradiate the LC cell. The spot size of the light source is 5 mm, which can cover the formation area of the etched spacers to evaluate the contrast ratio correctly. Results were compared with those of Fujikake *et al.*,[6] who used a polymer-stabilized ferroelectric liquid crystal in flexible displays to attain contrast ratios of up to 100 : 1. To our knowledge, our microcell LCD film has the highest contrast ratio among flexible LCDs. The contrasts of the other pitch devices are approximately 150. The highest contrast for the 100-μm-pitch sample was a consequence of increasing cell

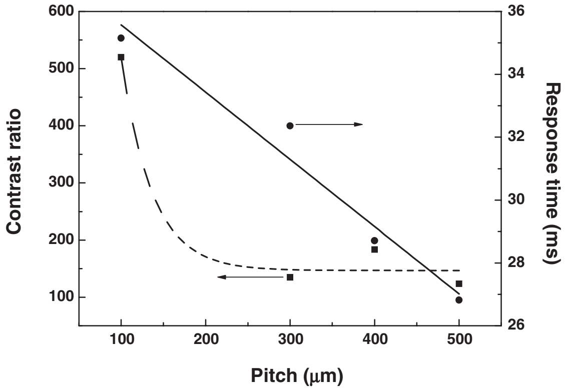


Fig. 5. Contrast ratio (left axis) and response time (right axis) as functions of pitch of cross-matrix photospacer.

gap uniformity by increasing the density of the cross-shaped spacers. The light leakage effect can be supressed by decreasing the deviation in the LC cell gap; therefore, the contrast ratio increases by increasing the cell gap uniformity owing to the increase in the density of the cross-shaped spacers used for enhancing cell gap uniformity. Compared with those of LC cells using glass substrates and etched spacers of 10 μm width, the contrast ratio of 800 : 1 measured for the glass substrate LC cell indicates that the higher cell gap uniformity gives rise to a higher contrast ratio. Although light leakage occurs near the etched spacers, increasing the density of the wall results in a smaller domain in the LC cell and the disclination lines within the smaller domain are fixed. The disclination lines occur in the neighborhood of spacers, as shown in Fig. 6. The width of the disclination lines for low-density spacers, with 400 μm pitch and a wall width of 40 μm, as shown in Fig. 6(a), is larger than that for high-density spacers with 100 μm pitch and a wall width of 10 μm, as shown in Fig. 6(b). Moreover, the width of the disclination lines under high-density spacers slightly changes by increasing applied voltage, but the width of the disclination lines for low-density spacers increases with increasing applied voltage. Therefore, these fixed disclination lines cause a high contrast ratio when transmission measurement is performed on a LC cell. Such a result also implies that a flexible LCD film can be used in video applications. The only difference in *V–T* curves between the flexible-substrate device and the glass-substrate device is a small optical bump above the threshold voltage in the curve of the flexible test cell. The difference is mainly due to a cell gap variation in the flexible LCD. VA cells with the same structure were fabricated at the same time using the flexible and glass substrates whose *V–T* curves are shown in Fig. 4(b). The threshold voltage and saturated voltage are about 2.3 and 4.0 V for the flexible device, respectively, and the maximum contrast ratio is the same as that of the TN device. The threshold voltage is the same for both the flexible device and the glass substrate device. However, the transmission decreases when the applied voltage is above the saturated voltage of the flexible device, because the real cell gap exceeds the optimally designed value in the lamination process, resulting in a phase retardation of the LCs exceeding 90°. This ratiocination could be proved by the phenomenon that the saturation voltage of the flexible device is smaller than that of the glass substrate device (open circles).

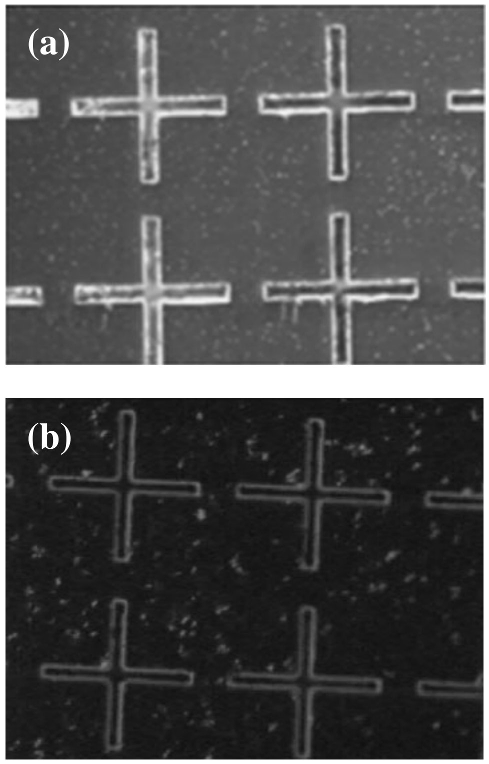


Fig. 6. Dark states of LC test cells driven at 5 V for (a) 400-μm-pitch spacers and (b) 100-μm-pitch spacers.

The response times (right axis) of the TN samples with various pitches of the cross spacer were also measured by the Otsuka LCD5100 system, as shown in Fig. 5. Note that the total response time, which is the sum of the rise time and decay time, is linear as a function of the pitch of the cross spacer. The response time decreases with increasing pitch of the spacer. The decrease in response time was due to the decreasing anchoring force at the lower-density spacers of the polymer wall. Among the flexible TN test cells, the response time is in the range between 20 and 40 ms, indicating that the microcell display can be used for flexible LCDs with a reasonable display performance. Nevertheless, the flexible device with 100-μm-pitch spacers has a maximum contrast ratio of 500, as shown by the left axis of Fig. 5. From the experimental results, we have shown that microcell technology with an excellent alignment effect in both the TN- and VA-modes is a good candidate for portable applications using flexible LCDs.

4. Conclusions

We have successfully developed and fabricated a new device using microcell flexible LCD film technology. The fabricated microcell flexible device, which features the highest contrast, an acceptable response, a light weight, and a wide viewing angle, is suitable for high-quality prototype displays. By optimizing the density of cross-type spacers, an acceptable response time and a high contrast ratio were obtained simultaneously. An improvement in the response time by redesigning the geometry of the spacer without decreasing the contrast ratio is necessary for high-quality video displays including flexible LCDs. Furthermore, flexible LCDs can be achieved using microstructure replication technology with suitable alignment treatments used in the glass-based LC process, and their electrooptical characteristics are almost the same as those of a microcell LC structure formed between two glass substrates. The cell gap between two flexible substrates can be well maintained by the crossed photospacers, and this device shows very high mechanical stability against external bending. The excellent optical performance reveals the possibility of making high-quality flexible displays, which means that the cost of flexible LCDs can be substantially reduced.

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