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Random and position-controlled 4-domain CTN-LCDs with wide viewing angle

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We have developed two types of 4-domain complementary TN (CTN) LCDs: a random type and a position-controlled type. The LC layer in each of the 4-domain CTN-LCDs is divided into four kinds of domain, each of which has a different combination of twist and tilt directions. The 4-domain CTN-LCDs have wide viewing angle characteristics and high contrast ratio without light masking layers. In the fabrication, each of their substrates was rubbed in only one direction; no additional step was required, in contrast to the conventional TN-LCD process. We have also fabricated 4-domain CTN TFT panels and confirmed that they have wide viewing angle characteristics without grey scale inversion.

1. Introduction

While twisted nematic (TN) mode LCDs provide a high contrast ratio at low driving voltage, their narrow viewing angle is a serious drawback. This narrow viewing angle is attributable to the asymmetric configuration of the liquid crystal (LC) molecules under applied voltage conditions. The viewing angle can be improved by dividing the pixel into domains in such a way that the domains compensate mutually in terms of their optical characteristics. Such pixel dividing techniques have been reported by several researchers: Yang [1], Takatori *et al.* [2] and Koike *et al.* [3] reported 2-domain TN-LCDs; Chen *et al.* [4] and Sugiyama *et al.* [5] reported 4-domain TN-LCDs. However, all of these multi-domain TN-LCDs need to be fabricated by unconventional processes, i.e. the photolithography process and the multiple rubbing process [2, 3], the SiO_x oblique evaporation process [4] and the polarized UV irradiation process [5]. Furthermore, some need a light masking layer to achieve a high contrast ratio. On the other hand, in-plane-switching mode LCDs have wide viewing angle characteristics [6]. However, these LCDs are not unsuitable for portable displays since their aperture ratio is low and high power consumption is necessary.

In this study, we have developed new 4-domain CTN-LCDs that have a wide viewing angle and high contrast ratio and can be fabricated by essentially the same process as conventional TN-LCDs. We also report here the high performance of the 4-domain CTN TFT panel.

2. Structure

We have developed two types of 4-domain CTN-LCDs: a random type and a position-controlled type. Figure 1 (*a*) depicts a random 4-domain CTN-LCD. The LC molecules illustrated are those at a middle depth

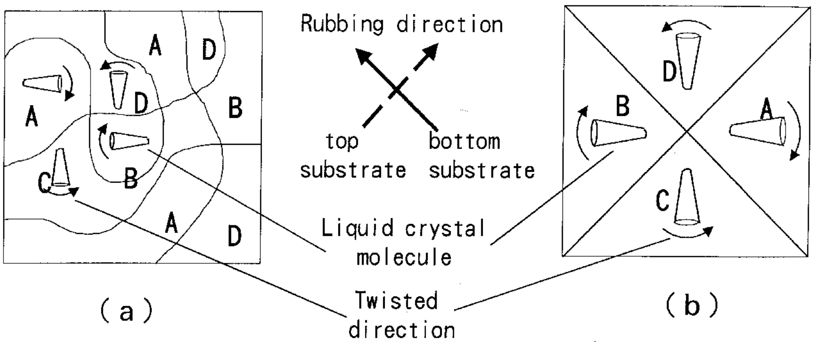

Figure 1. Illustrations of 4-domain CTN-LCDs. LC molecules at a middle depth of the LC layer are illustrated: (*a*) random type, (*b*) position-controlled type.

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of the LC layer. The random 4-domain CTN-LCD is divided into four kinds of domain—A, B, C and D—each of which has a different combination of twist and tilt directions. This provides the 4-domain CTN-LCDs with a wide viewing angle. Figure 1 (*b*) illustrates the position-controlled 4-domain CTN-LCD, which is also divided into four different domains; in this case, however, domain division is well controlled, and all domains are equal in area.

3. Fabrication

3.1. *Material*

The LC in the 4-domain CTN-LCDs is a conventional nematic LC, but containing no chiral dopants. The alignment layer has a very low pretilt angle (practically 0° because the LC aligns perpendicular to the rubbing direction) and is rubbed in only one direction, which is essentially the same process as used in the fabrication of conventional TN-LCDs (see figure 1).

Because the LC is free of chiral dopants, each of the two twist directions appears with the same probability. Because the alignment layer has a very low pretilt angle, the two tilt directions also appear with the same probability under applied voltage conditions.

3.2. *Processes and mechanisms*

The mechanism which produces the four kinds of domain in the LC layer is as follows. The LC layer between two substrates is first heated to a temperature higher than its nematic–isotropic transition temperature (T_{NI}). The LC layer is subsequently cooled to a temperature lower than the T_{NI}; in the cooling process, nematic droplets begin to appear. The directions of the LC directors in the individual droplets are initially random. With droplets gradually growing, they eventually reach the alignment layer. The LC twist and tilt directions, which depend on the direction of the LC director in individual droplets, become fixed as droplets reach the alignment layers. As a result, two twist and two tilt direction regions appear randomly depending on the randomness of the directors in the droplets.

The fabrication method for the position-controlled 4-domain LCDs is the same as that for the random 4-domain LCDs except for the application of a non-uniform

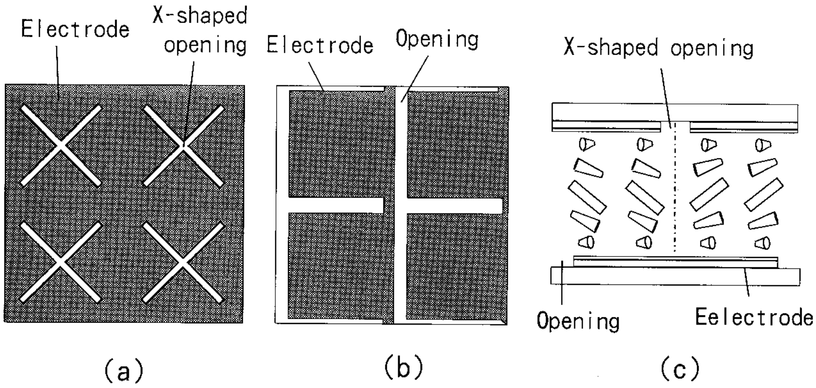

Figure 2. Electrode structure and cross-sectional view of position-controlled 4-domain CTN-LCD: (*a*) top electrode, (*b*) bottom electrode, (*c*) cross-sectional view. (*a*) and (*b*) show the area of four pixels.

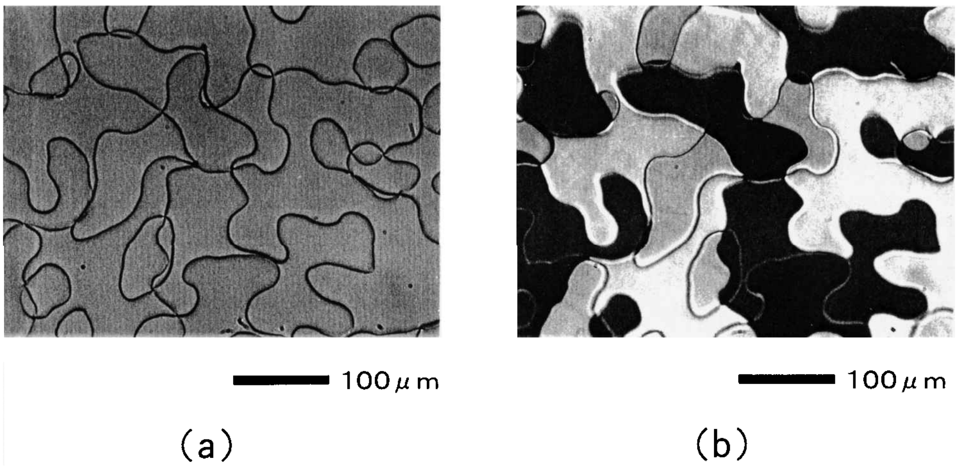

Figure 3. Micrographs of a random 4-domain CTN-LCD: (*a*) in a crossed Nicol state, (*b*) in an uncrossed Nicol state, where the test cell was tilted and voltage was applied.

electric field in the cooling process, by which each pixel is divided into the four equal-area domains shown in figure 1 (*b*).

4. Experimental

For both types of 4-domain CTN-LCDs, we used conventional nematic LC materials without chiral dopants and an alignment layer with a very low pretilt angle.

The fabrication of the random and position-controlled 4-domain CTN-LCDs was as follows. The substrates used in random 4-domain CTN-LCD experiments had electrodes of 10 mm diameter. In the position-controlled 4-domain CTN-LCD experiments, we used a pair of substrates which had top electrodes with the X-shaped openings illustrated in figure 2 (*a*) and bottom electrodes with openings of the pattern illustrated in figure 2 (*b*). By the use of these substrates, we were able to obtain a non-uniform electric field between the two electrodes. Figure 2 (*c*) shows a cross-sectional view of the resulting position-controlled 4-domain CTN-LCD.

The substrates which were covered with the alignment layer were rubbed with a roller. A pair of the substrates were combined to make a test cell; the rubbing

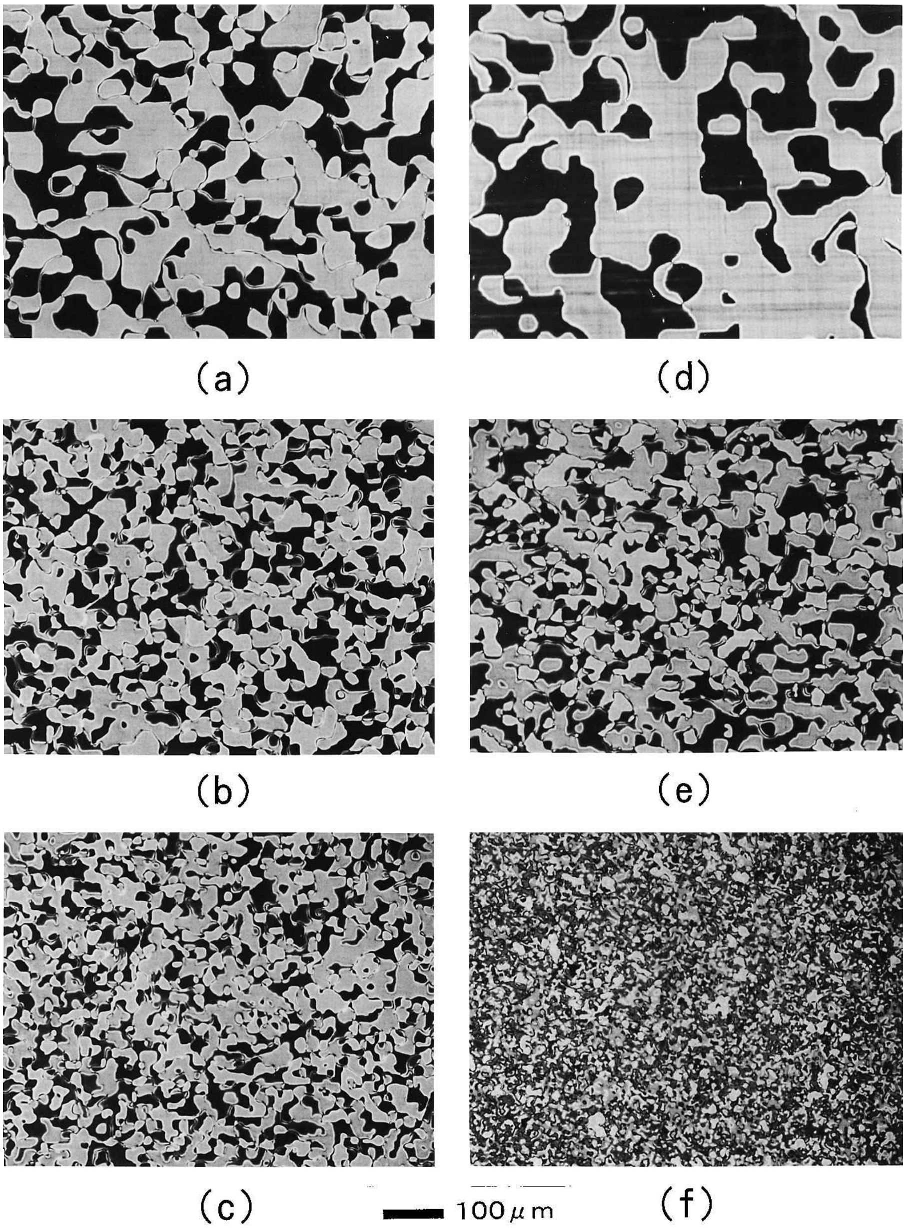

Figure 4. Domain size dependence on cooling rate and applied voltage: (*a*) $-5°C\ min^{-1}$, 20 V, (*b*) $-20°C\ min^{-1}$, 10 V, (*c*) $-50°C\ min^{-1}$, 10 V, (*d*) $-5°C\ min^{-1}$, 0 V, (*e*) $-20°C\ min^{-1}$, 20 V, (*f*) $-20°C\ min^{-1}$, 50 V.

directions of the two substrates were at right angles. The cell thickness was 5 μm for both types of 4-domain CTN-LCDs.

The LC was then introduced into the test cell. The test cell was heated to a temperature higher than T_{NI}, and then cooled to a temperature lower than T_{NI}, during which time voltages were applied. Electrode structure determined which type of the 4-domain CTN-LCDs was obtained.

5. Results and discussion

5.1. *Random 4-domain CTN-LCDs*

Figure 3 (*a*) and 3 (*b*) are micrographs of a random 4-domain CTN-LCD. Figure 3 (*a*) was taken in a crossed Nicol state, under conditions of no applied voltage; figure 3 (*b*) was taken in an uncrossed Nicol state, where the test cell was tilted and voltage was applied.

Figure 3 (*b*) shows clearly four kinds of domain existing in a random pattern, and figure 3 (*a*) shows that the four kinds of domain have equal transmittance in the direction perpendicular to the substrate. These domains are fairly stable below T_{NI}. When the cell was heated to a temperature higher than its T_{NI}, the domains disappeared and new domains appeared in the subsequent cooling process.

The domain size of the random 4-domain CTN-LCD can be controlled by cooling rate and the magnitude of the applied voltage. Figure 4 shows that the domain size is dependent on cooling rate and magnitude of the applied voltage. As can be seen, the larger the cooling rate and applied voltage, the smaller the domain size. The domain size can be controlled over a wide range.

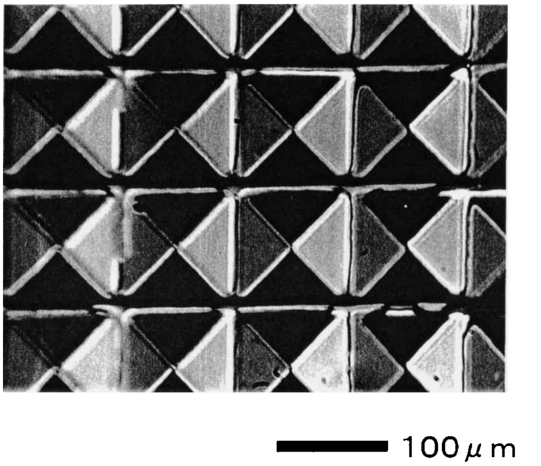

Figure 5. Micrograph of a position-controlled 4-domain CTN-LCD: taken in an uncrossed Nicol state, where the test cell was tilted and voltage was applied.

5.2. *Position-controlled 4-domain CTN-LCDs*

Figure 5 shows a micrograph of a position-controlled 4-domain CTN-LCD; it was taken in an uncrossed Nicol state, where the test cell was tilted and voltage was applied. As can be seen, the domain division is well controlled, and each pixel is divided into four equal area domains.

5.3. *Domain boundary*

One outstanding property of both types of the 4-domain CTN-LCDs is that the boundary lines between the domains do not transmit light. This enables the 4-domain CTN-LCDs to show a high contrast ratio with no need for light masking layers. The reason for this high contrast ratio is as follows. There are two types of boundary, that between two domains having the same twist direction but opposite tilt directions (we call this the 'R-boundary'), and that between two domains having different twist directions (we call this the 'T-boundary'). The former has light transmission properties while the latter does not (in a normally white mode).

The LC configurations of these two kinds of boundary are shown in figure 6. Figure 6 (*a*) represents

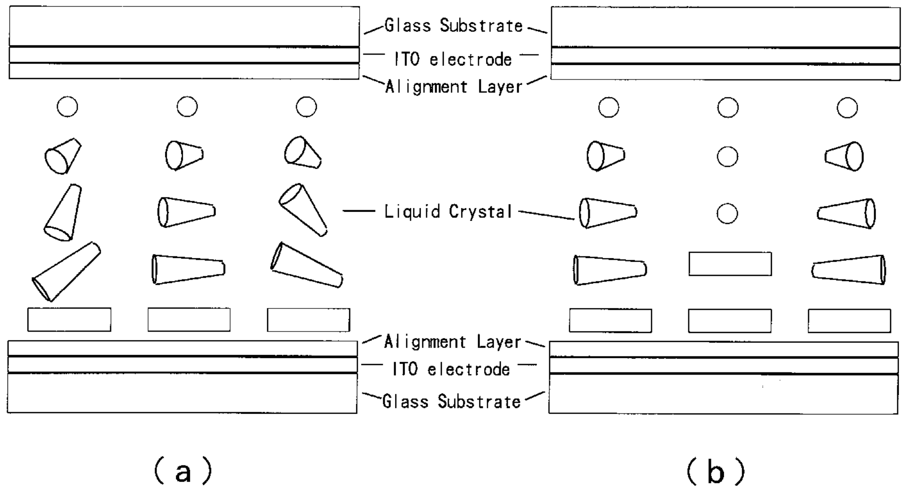

Figure 6. Illustration of boundaries: (*a*) R-boundary, a boundary exists between two domains having the same twist direction but opposite tilt directions, under applied voltage condition; (*b*) T-boundary, a boundary exists between two domains having different twist directions, under no applied voltage condition.

the R-boundary under applied voltage; figure 6 (*b*) represents the T-boundary with no applied voltage. Even when the voltage is applied, the LC molecules in the R-boundary keep the initial state (i.e. no applied voltage condition), though the LC molecules in the other regions respond to the applied voltage, figure 6 (*a*). As a result, the polarization plane of the incident light rotates in the R-boundary and polarized light passes through the analyser. On the other hand, the LC molecules in the T-boundary do not have a continuous 90° twist, so that the polarization plane of the incident light does not rotate and polarized light cannot pass through the analyser, figure 6 (*b*).

In 4-domain CTN-LCDs, the two domains which have the same twist direction and different tilt directions are not in contact with each other (A–C, B–D in figure 1). This means that polarized light which transmits through the boundary lines cannot pass through the analyser; consequently, the 4-domain CTN-LCDs have a high contrast ratio even without a light masking layer.

In our experiments, all test cell and TFT panels were cooled under applied voltage conditions.

5.4. *Dual-domain type random CTN-LCDs*

To confirm the tendency of T-boundaries to appear in the cooling process under applied voltage conditions, we tried to fabricate dual-domain type random CTN-LCDs. The CTN-LCD has a region with opposite twist direction between domains which have the same twist direction but opposite tilt directions. In experiments, a small amount of chiral dopant was added to the LC to obtain domains which favour a single twist direction.

Figure 7 shows micrographs of the dual-domain type CTN-LCD. They were taken in an uncrossed Nicol state, the test cell was tilted and voltage was applied. The regions with opposite twist directions are observed as black regions. As shown in figure 7, regions with opposite twist directions exist between domains which have the same twist direction but opposite tilt directions. Thus, only T-boundaries appear in this CTN-LCD. This result shows the tendency of T-boundaries to appear in the cooling process under applied voltage conditions.

5.5. *Electro-optic properties*

Figure 8 shows a transmittance/voltage curve of a random 4-domain CTN-LCD. This type of LCD can be operated at less than 5 V, nearly the same level as that of a conventional TN-LCD. In spite of the absence of a light masking layer over the boundaries, the contrast ratio of the 4-domain CTN-LCD is 200 : 1 at 5 V.

6. TFT panels

6.1. *Fabrication*

Using the same principle as for the test cells, we fabricated 4-domain CTN TFT panels. In fabricating TFT panels designed to realize the high performance found in the test cells, we used the same LC and the same alignment layer as for the test cells. Each of

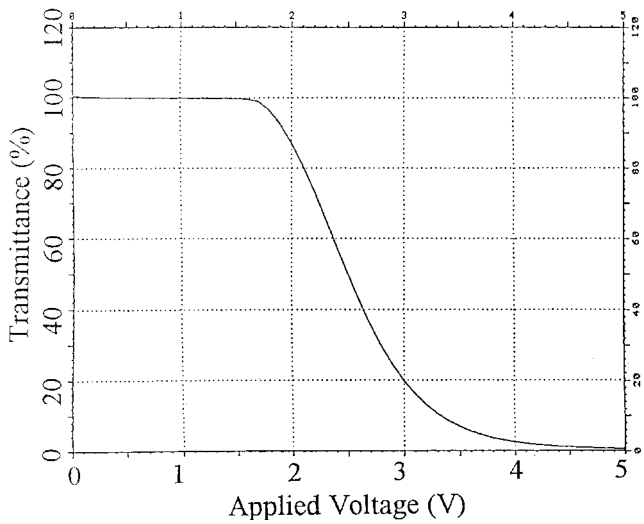

Figure 8. Transmittance/voltage curve of the random 4-domain CTN-LCD.

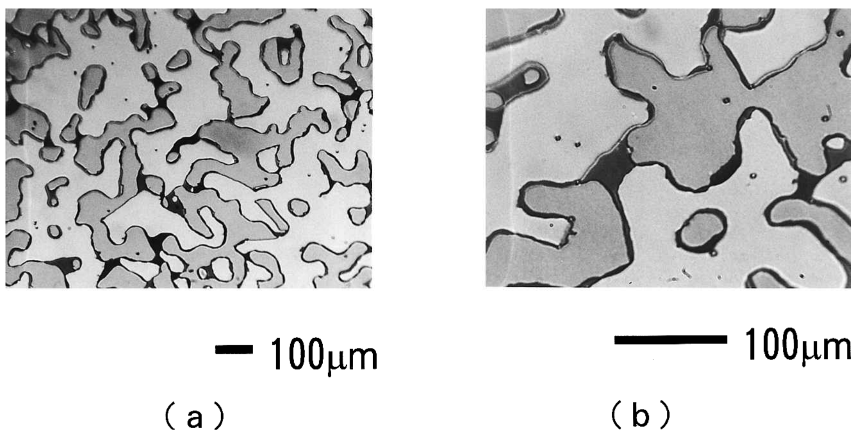

Figure 7. Micrographs of dual-domain type random CTN-LCD. The photographs were taken in an uncrossed Nicol state, where the test cell was tilted and voltage was applied: (*a*) and (*b*) are in different magnification.

the substrates was covered with the alignment layer and then rubbed only once. After introduction of the LC, the panel was heated to a temperature higher than T_{NI}, then cooled to a temperature lower than T_{NI}, during which time a voltage was applied.

6.2. *Viewing characteristics*

The specifications of the CTN TFT panel are given in the table.

The images produced by both the position-controlled and the random 4-domain CTN TFT panels are good when viewed in a direction perpendicular to the substrate. The random 4-domain CTN-TFT panel images, however, appear coarse-grained when viewed from an oblique direction: this is because of the unequal domain areas per pixel. Position-controlled 4-domain CTN-LCD images are good even when viewed from an oblique direction.

Figures 9 and 10 are photographs of a 4-domain CTN TFT panel and a conventional TN TFT panel, respectively. Viewing angles are 0°, 30° and 50°, and the azimuthal angles are at 45° intervals.

In a conventional TN panel, images tend to darken when viewed from below, and to whiten when viewed from above. In contrast, the 4-domain CTN TFT panel

Table. Specification of the 4-domain CTN TFT panel.

Parameter	Value
Display area	9·4 inch diagonal
Number of pixels	VGA (640 × RGB × 480)
Pixel size	300 μm × 100 μm
Number of colours	4096
Viewing angle[a]	up–down: >100 right–left: >100
Response times	rise: 15 ms decay: 20 ms

[a] Contrast ratio >5 and no grey scale inversion.

Figure 9. Photographs of a 4-domain CTN TFT panel. Viewing angles are 0° (centre), 30° (middle) and 50° (outer); azimuthal angles are at 45° intervals.

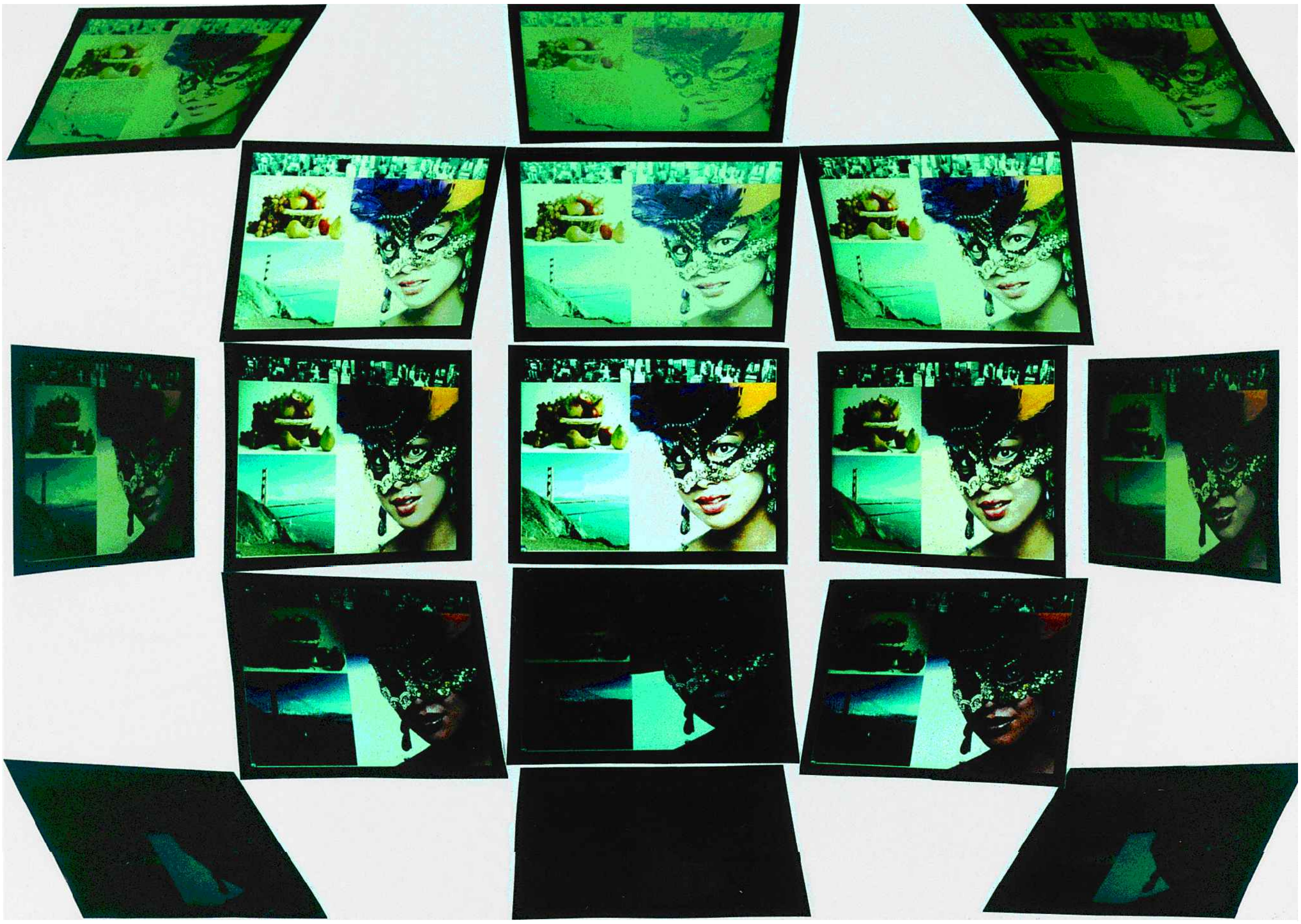

Figure 10. Photographs of a conventional TN TFT panel. Viewing angles are 0° (centre), 30° (middle) and 50° (outer); azimuthal angles are at 45° intervals.

gives a good image in all directions. Moreover the 4-domain CTN TFT panel shows no grey scale inversion even at a 50° viewing angle, while a conventional TN panel shows grey scale inversion even at a very small viewing angle.

Figure 11 shows the dependence of luminance on viewing angle in the 4-domain CTN TFT panel. The 100% level is defined as the luminance in the direction perpendicular to the panel. As shown in figure 11, the dependence of luminance on viewing angle is almost the same in all azimuthal angles. The 4-domain CTN TFT panel has no grey scale inversion and excellent grey scale characteristics throughout the entire viewing region. These results are consistent with the photographs shown in figure 9.

6.3. *Response time*

The rise time (time required to go from 90% to 10% transmittance) of the 4-domain CTN TFT panel, is slightly less than that of conventional TN panels (20 ms). The decay time (time required to go from 10% to 90% transmittance) is much shorter than that of conventional TN panels (50 ms). This short response time is assumed to be due to the presence of distortion energy in the domain boundary regions.

7. Conclusion

We have developed two new types of 4-domain CTN-LCDs: a random type and a position-controlled type. The LC layer in each of the 4-domain CTN-LCDs is divided during cooling into four kinds of domain, each of which has a different combination of twist and tilt directions. The 4-domain CTN-LCDs have wide viewing angle characteristics and achieve a high contrast ratio without light masking layers.

We have also fabricated 4-domain TFT-LCD panels. These novel CTN TFT-LCD panels have wide viewing angle characteristics without grey scale inversion throughout the entire viewing region. In fabrication, each of their substrates was rubbed in only one direction: no additional step was required, in contrast to conventional TN-LCDs.

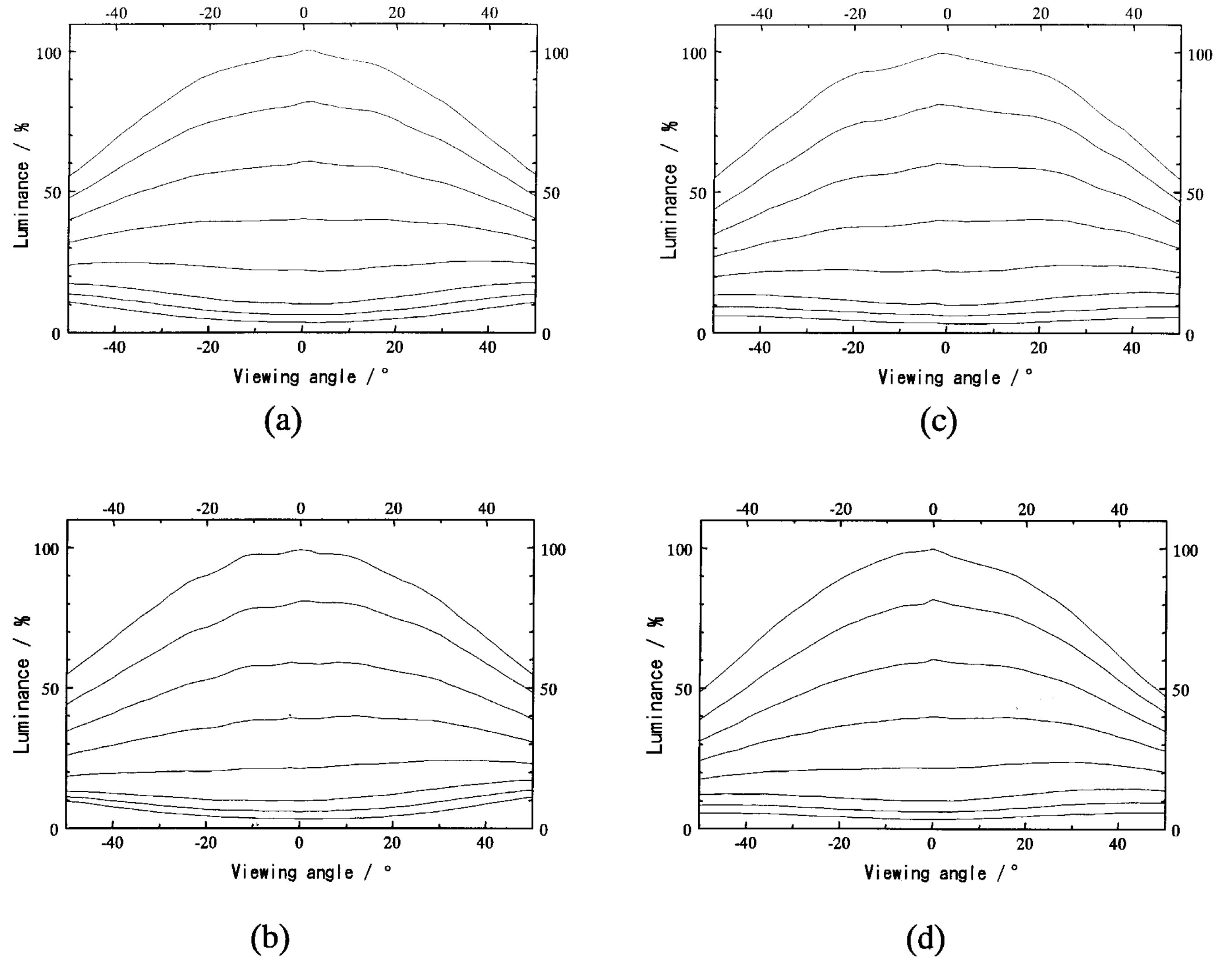

Figure 11. The dependence of luminance on the viewing angle of the 4-domain CTN TFT panel: (*a*) up–down, (*b*) right–left, (*c*) up right–down left, (*d*) up left–down right.

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