Stabilization of the liquid crystal director in the patterned vertical alignment mode through formation of pretilt angle by reactive mesogen

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In the patterned vertical alignment (PVA) cell in which multidomains are formed from the perfect vertical alignment through an oblique field only, the formation of disclinations between liquid crystal (LC) molecules is inevitable in the presence of an electric field, which lowers transmittance and the response time. In the proposed PVA device, the pretilt angle is formed in four different directions through the polymerization of an UV curable reactive mesogen monomer at the surface. In this way, the reorientation of LC responding to an electric field is well defined, and thus the device shows reduced threshold voltage and much improved response time in all gray scales.
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Recently, the flat-panel displays of various kinds are continually increasing the market share in displays. Among those, the liquid crystal displays (LCDs), which range in the panel size from large for LCD television (TV) to small size for the mobile phone applications, have been adequately fabricated to meet the customers' request. In the LCD TVs, several LC modes such as in-plane switching,[1] fringe-field switching,[2–4] multidomain vertical alignment (MVA),[5] and patterned vertical alignment (PVA) (Refs. 6–8) are adopted to exhibit a high image quality. Among them, PVA shows a very high contrast ratio at normal direction because the LC is perfectly vertically aligned against the substrate.

In the PVA mode, the optical transmittance of the vertically aligned nematic LC layer between crossed polarizers can be given as

$$T = \sin^2\{2\phi(V)\}\sin^2 \frac{\Gamma(V)}{2}, \quad (1)$$

where $\phi(V)$ is voltage-dependent azimuthal component of the angle between the LC optic axis and the transmission axes of the crossed polarizer and $\Gamma(V)$ is voltage-dependent retardation of the LC layer equal to $2\pi d\Delta n(V)/\lambda$ (d is the thickness of LC layer, Δn is the birefringence value of the LC, and λ is the wavelength of an incident light). In the absence of an electric field, $\phi(V)$ and $\Gamma(V)$ are zero so that the cell appears dark. With bias voltage, the vertically aligned LC directors (LCs) tilt downward making the conditions of $\phi(V)=\pi/4$ and $\Gamma(V)=\pi$ to maximize the light efficiency as T is equal to 1.

In a typical PVA panel, the pixel and common electrodes are patterned alternatively, and thus an oblique field which has vertical and horizontal components is generated with biased the voltage and this applied field tilts LCs downward in four different diagonal directions, as shown in Fig. 1. In order for LCs to tilt downward exactly in diagonal directions, the field direction of horizontal component of an oblique field should be in diagonal direction. However, in a real pixel structure as shown in Fig. 1(a), the interference of unwanted electric field from signal lines as well pixel edge exists and, hence, the generation of disclinations between LC molecules are inevitable, causing several defect points $S=+1$ with dark disclination lines which come from the fact that the LC remains vertically aligned between the domains. The existence of disclination lines and defect points will decrease the transmittance and increase the response time. To solve this problem, various pixel structures were proposed.[9,10] In addition, since the LC tilts downward from perfect vertical alignment only by an oblique field, the response time in low gray levels is very slow and it strongly depends on the intensity of applied electric fields, which causes a problem that the response time is strongly a gray scale dependent. In order to improve this slow response time in the PVA mode, the overdriving technology through the dynamic capacitance

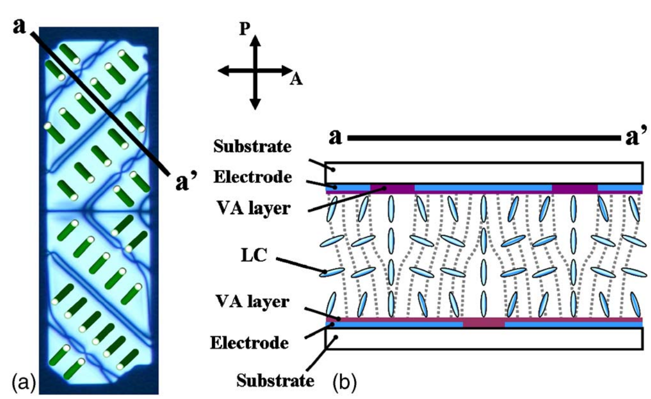

FIG. 1. (Color online) (a) Optical microphotograph of a pixel in the white state of the PVA cell with schematic drawing of LCs and (b) schematic cross-section view of the cell along a-a'.

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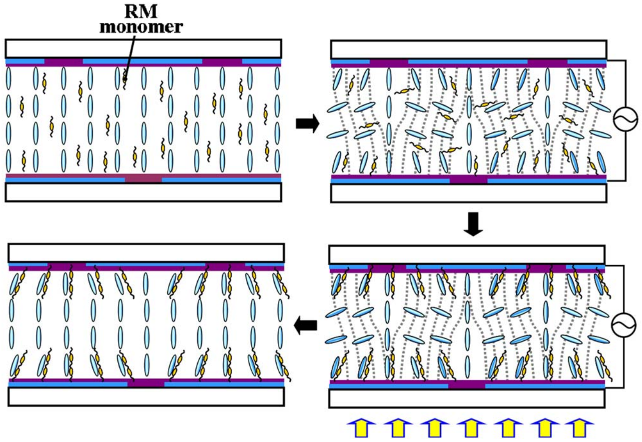

FIG. 2. (Color online) Schematic drawing of the PVA cell exhibiting how the pretilt angle is formed using RM monomer.

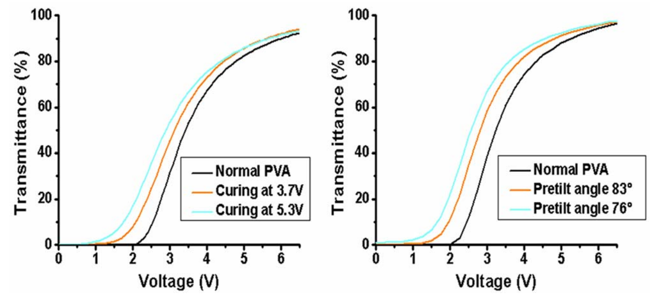

FIG. 3. (Color online) (a) Measured voltage-dependent transmittance of the proposed PVA cell as a function of applied voltage during UV curing and (b) calculated voltage-dependent transmittance of normal PVA cell as a function of surface pretilt angles.

compensation [DCC (Refs. 11 and 12) and DCC II (Refs. 13 and 14)] was proposed; however, this induces the additional cost in devices. On the other hand, in the MVA mode, a pixel electrode is patterned like in the PVA mode, however, instead of patterning the common electrode on top substrate, the protrusion is used, in general. In order to remove the protrusion while improving the transmittance, the contrast ratio and response time, the polymer sustained alignment technology[15] which generates multipretilted LCs was adapted to the MVA mode and the device showed improved transmittance and fast response time in low gray scale.

Since the nature of PVA mode has intrinsic problems such as low transmittance, slow response time, and strong gray scale dependency of the rising time at the high operating voltage, the control of tilt angle on the vertical alignment in four different directions has been investigated. For this purpose, we used an UV curable reactive mesogen (RM) monomer. At first, the RM monomer and photoinitiator with proper amount were mixed with a superfluorinated LC mixture (negative dielectric anisotropy $\Delta\varepsilon = -4$, birefringence $\Delta n = 0.077$ at $\lambda = 589$ nm, Merck). The whole mixture was filled into the PVA cell where the cell gap was 3.8 μm and both surfaces have the vertical alignment layer with patterned electrodes, as shown in Fig. 2.

At an initial state, the RM monomer and the LCs are vertically aligned. Then, a voltage larger than the Freedericksz transition voltage (V_{th}) is applied to the cell so that the RM monomer as well as LC reorients with a slight tilt angle from the vertical alignment in response to an electric field. At this state, the PVA cell was exposed to the UV light. Then the RM monomers are polymerized with constant angle tilted on the surface of substrate and thus the pretilt layer in the cell is formed and continuously remains at this state even after removing the voltage. In this way, the pretilt angle could be controlled on the surface of vertical alignment layer even without rubbing the substrate.

With different curing conditions such as the curing time and voltage applied to the cell, and weight percent ratio of the RM to the LC, we fabricated several PVA cells. Figure 3(a) shows measured voltage-dependent transmittance (V-T) curves of the PVA cell as a function of curing voltages. While normal PVA cell shows that V_{th} is 2.4 V, the cell cured at 3.7 V shows V_{th} of 1.9 V. In addition, when the curing voltage is high enough such as 5.3 V, the V_{th} becomes less than 1.9 V, as well as with much improved transmittance. In order to understand the changes in V-T curves in the RM-doped cells, we performed two-dimensional simulations of the normal PVA cells using LCD Master (Shintech from Japan) to achieve V-T curves as a function of the pretilt angle in each domain. According to the result of simulation, the pretilt angle of the LC in each domain was assumed to have 83° and 76° when the RM monomer was cured at 3.7 and 5.3 V, respectively, and the corresponding trend of V-T changes was shown in Fig. 3(b). With increased in pretilt angle, the V-T curve shifts to the left and the transmittance increase. As clearly indicated, the V_{th} was larger than 2 V in the normal PVA cell but it is decreased to less than 2 and 1 V when the pretilt angles were 83° and 76°, respectively. The theoretical result is in good agreement with experimental result and is a good indication that the RM monomer is polymerized on the surface not in the bulk. One noticeable thing is that if the PVA cell has a tilt angle of 76° at 5.3 V with $\phi(V) = \pi/4$, then $\Gamma(V)$ is large enough to generate a light leakage at the dark state. The light leakage will lower contrast ratio of the device at normal direction which is not a favorable condition.

In order to investigate that whether the stability of voltage-dependent LC reorientation is improved in the device with defined pretilt angle or not, time-resolved LC textures by applying two different voltages to reach a transmittances of 50% (T_{50}) and 90% (T_{90}) of maximum transmittance were observed and compared between the cells, as shown in Fig. 4. In the normal PVA cells, the formation of disclinations between patterned electrodes is clearly observed before the texture is stabilized in both gray scales, generating dark lines or spots during switching (see textures inside white lines). However, in cells with defined pretilt angle that is not observed, instead, the transmittance of the cell is changed as the time evolves, while the texture remains the same. When the voltage is applied, the rising times T_{50} and T_{90} to reach stabilized texture in the conventional cell are 34 and 16.2 ms, respectively, however, in the proposed cell, they are reduced to 17.1 and 4.1 ms. The result clearly indicates that the proposed cell minimizes the formation of disclinations between domains, improving the rising time of the PVA mode.

Finally, the response times of both types of cells are measured with different gray scales, as shown in Fig. 5. The rising time of the proposed PVA cell is about two times faster than that of the normal PVA cell. In case of decaying time,

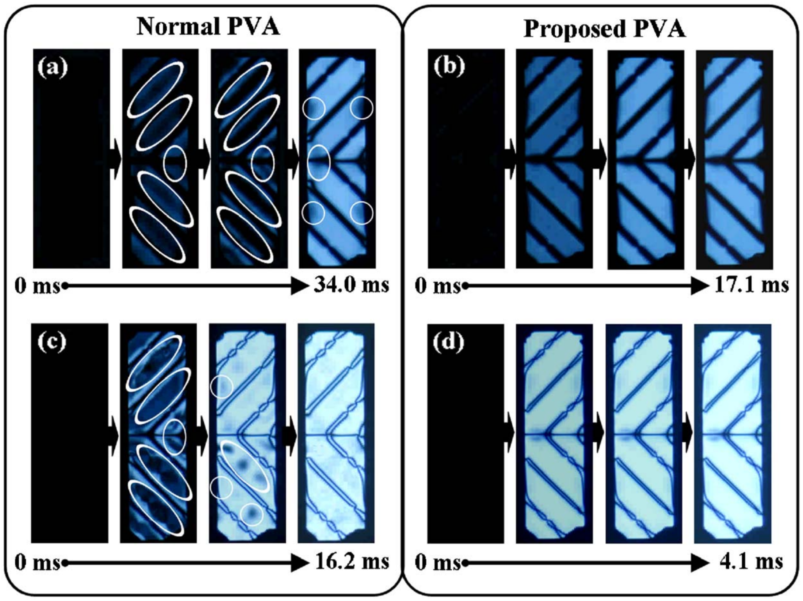

FIG. 4. (Color online) Comparison between normal PVA and proposed PVA for time-resolved LC textures and rising time: (a) and (b) are for T_{50} and (c) and (d) are for T_{90}, respectively.

the cell cured at 3.7 V exhibits a similar response time to thee normal cell; however, the cell cured at 5.3 V shows slower response time than that of normal cell because of too high tilt angle from vertical alignment.

In summary, the PVA cell with defined pretilt angles in multidirections was achieved using RM monomer. The pretilt angle from vertical alignment was defined by controlling the applied voltages above the threshold. The proper tilt angle from the vertical alignment is important to improve electro-optic characteristics while keeping a high contrast ratio at normal direction. The optimized cell shows decreased threshold voltage and drastic improvement in the rising time.

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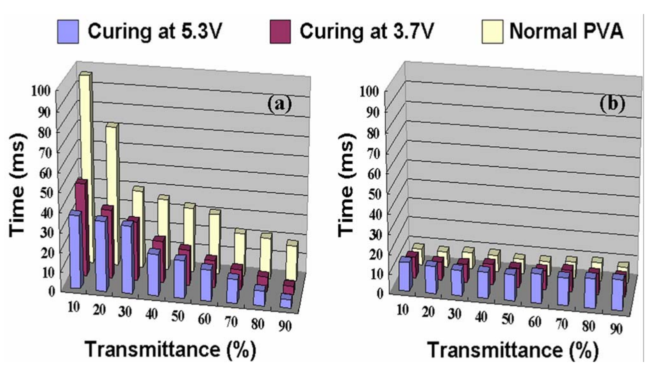

FIG. 5. (Color online) Comparison of (a) rising and (b) decaying gray level response times between normal and proposed PVA cells.

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