Plasma-beam alignment technique for ferroelectric liquid crystals

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Abstract — The plasma-beam alignment procedure earlier developed for the alignment of nematic liquid crystals is successfully extended to ferroelectric liquid crystals (FLC). The highly uniform alignment of the "chevron" structure (before electrical treatment of FLC cells) and "quasi bookshelf" structure (after the electrical treatment) are realized. The contrast of bistable switching larger than 350:1 is achieved. This makes the non-contact plasma-beam alignment procedure especially attractive for high-contrast bistable LCDs on an LCOS base, particularly used in PDA and e-books. Fast switching and realization of gray scale in the plasma-beam aligned FLC cells makes this technique also promising for full-color displays including color LCD TV.

Keywords — *Feroelectric liquid crystal, FLC LCD, FLC alignment, plasma-beam alignment, ion-beam alignment.*

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1 Introduction

The discovery of ferroelectricity of the chiral smectic-C phase (SmC*) by Mayer *et al.*[1] in 1975 and the practical realization of bistable electrical switching in these phases by Clark and Lagerwall[2] in 1980 were very influencial in the development of liquid-crystal displays (LCDs). The bistable switching in these materials, coined as ferroelectric liquid crystals (FLC), was realized in thin cells in which the helical structure was suppressed. The FLC-display prototypes excel in wide viewing angle, fast response time, and ultra-low power consumption, showing revolutionary improvements compared with present-day TN-LCDs. Because of this, FLC-LCDs are recognized as one of the most promising devices for future displays. Their potential is especially high for high-contrast LCDs used in portable devices and color television.

Despite their very high potential, FLC devices are still not commercialized mainly because of alignment problem. Good alignment of FLC cannot be easily attained, as in the case of nematic LC because of the layered helical structure. The alignment force will not only provide uniform alignment of the FLC layers, but also suppress the helix of the vector of spontaneous polarization. In practice, this problem is solved either by the introduction of aligned polymer networks (polymer-stabilized FLC)[3] or by proper treatment of the boundary substrates confining FLC film (surface-stabilized FLC). In the latter case, in parallel with traditional rubbing,[2] alternative alignment processes have been considered. Among them are photoalignment,[4,5] vapor deposition,[6,7] and ion-beam sputtering deposition[8] of the SiO_x layers. Special treatment of FLC cells, such as low-frequency ac field treatment[9] and treatment based on the temperature gradient,[10] are additionally used to improve alignment generated by these methods.

In the present paper, we consider a novel approach for the surface stabilization of FLC films. It consists of anisotropic etching of the alignment substrates by the obliquely incident beam of accelerated ions or plasma. Recently, this process was successfully applied for the alignment of conventional nematic LC[11–13] and "passive" LC such as reactive mesogens and semiconducting LC used in optical films and surface electronics.[14] This technique provides excellent alignment uniformity of LC on a macroscopic and microscopic scale, wide range variation in pretilt angle and anchoring energy, and good electro-optic performance. Two types of alignment of nematic LC were observed: easy axis in the plane of the plasma-beam incidence and perpendicular to this plane. These types of alignment were coined as the first and second alignment modes. The transition from the first to the second alignment mode was observed with increasing exposure dose.[15]

The present paper shows that plasma-beam alignment can also be successfully extended for the alignment of FLC. Alignment by this method results in FLC films having excellent uniformity and demonstrating high electro-optic contrast. The most effective applications of plasma-beam-aligned FLC layers are discussed.

2 Experimental details

2.1 Preparation of substrates

We used films of polyimide AL3046 from JSR for the bounding substrates. The polymer layers were spin-coated at 3000 rpm on glass slides (2 × 3 cm) containing patterned ITO electrodes and subsequently baked at 80°C for 5 min and then at 180°C for 1 hour. In the following, the substrates were processed by the plasma-beam alignment technique.

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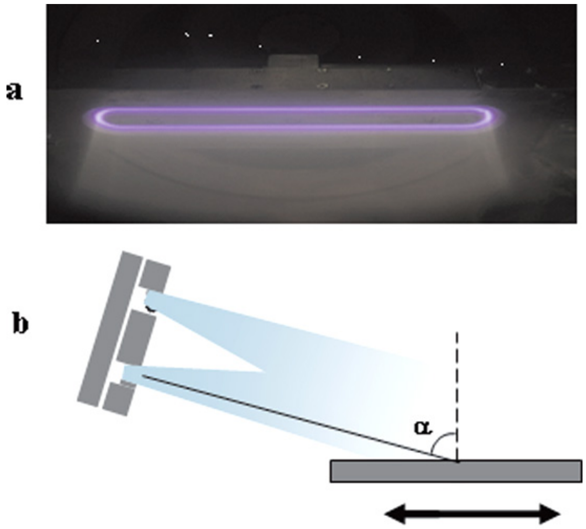

FIGURE 1 — (a) Photograph of anode layer source and generated plasma "sheets" and (b) geometry of plasma-beam irradiation of alignment substrates.

2.2 Treatment procedure

For irradiation, we used an anode layer source (ALS) with a racetrack-shaped glow-discharge area.[12,16] In the beam mode, this source generates two "sheets" of accelerated plasma with a width of 25 cm [Fig. 1(a)]. The device operated in the regime of low energies (E = 500–800 eV) and currents (j = 5–20 μA/cm^{2}). The source was set for oblique irradiation [Fig. 1(b)]. The incidence angle of the plasma beam was about 70°. The distance between the discharge area and treated substrates was about 20 cm. The substrate's holder was moved by the PC-controlled moving system providing cycling translation in the horizontal plane. The translation amplitude was 3 cm, while the translation speed was 2.5 mm/sec. The translation regime of irradiation provided uniform treatment over the entire substrate area. The treatment time was varied between 1 and 30 min. The surface morphology of the polyimide films was studied by using AFM device NanoScope IIIa from Digital Instruments working in the tapping mode.

2.3 FLC cells

For the alignment tests, the FLC cells were assembled with parallel alignment of plasma-treated substrates on both sides. The cell gap was maintained with 3-μm spacers. The cells were filled with FLC material FELIX 017/100 from Clariant. Phase transition temperatures of this material are I 87°C N 77°C S_A 73°C S_{C^*} –28°C X so that at ambient temperatures this material is in a ferroelectric chiral smectic C mesophase. FELIX 017/100 has spontaneous polarization around 47 nC/cm^{2}. The FLC was filled in the cells in isotropic phase. After filling, the cells were slowly cooled down with a speed of 1–2°C per minute up to room temperature.

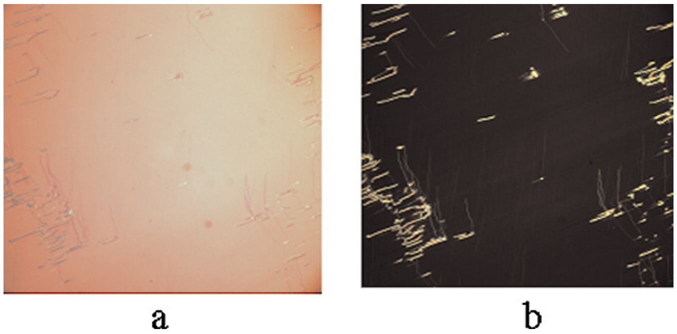

FIGURE 2 — Textures of FELIX-17 FLC layer aligned between two plasma-beam-processed PI substrates. (a) bright state; (b) dark state. No electrical treatment was preliminary applied.

2.4 Electro-optics measurements

Electro-optical measurements were carried out based on a He–Ne laser, DAQ board (PCI-MIO-16E-4 from National Instruments Corporation), voltage amplifier (Model: 7600 wideband amplifier from KROHN-HITE Corporation), and a rotating table for adjusting the angular position of the FLC cell placed between crossed polarizer's.[17] A special software program was developed for calculation of experimental data.

3 Results and discussion

3.1 FLC alignment

The FLC alignment on plasma-beam-treated substrates was observed for a wide range of exposure doses. However, the alignment quality was considerably better for the higher doses (15–30 min at j = 8–10 μA/cm^{2}), corresponding to the second-mode alignment of nematic LC. Because of this, high exposure doses were chosen in further work. Figure 2 shows a texture of FLC cells observed by a polarizing microscope under crossed polarizers. This is a chevron texture with high-alignment quality. The zigzag defects in this cell are practically eliminated. Presumably, smectic layers in this cell are in C1 geometry because of the moderate values of

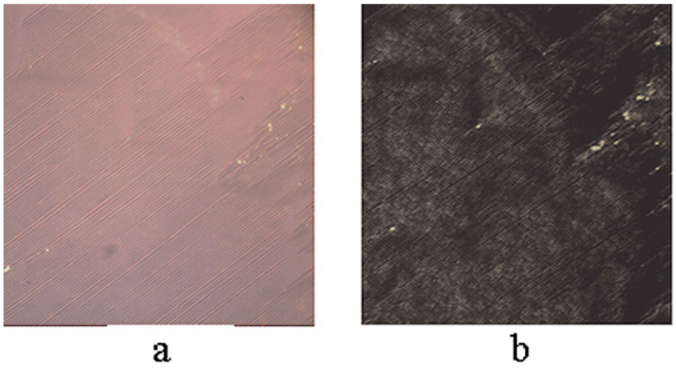

FIGURE 3 — Textures of FELIX-17 FLC layer aligned between two plasma-beam-processed PI substrates. (a) bright state; (b) dark state. Cell is preliminary treated with electric field.

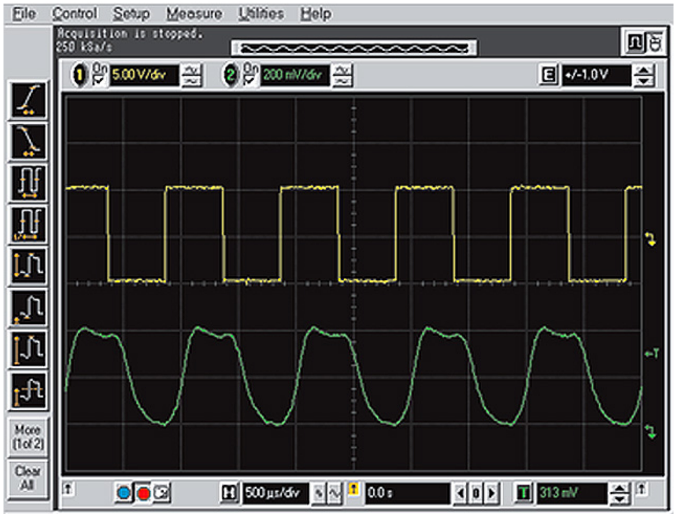

FIGURE 4 — Optical response of FLC cell on the rectangular driving signal with an amplitude 5 V and period of 1 msec.

azimuthal anchoring on plasma-beam-processed substrates.[18] Similarly to substrates subjected to other alignment treatments,[8] we observed structural transition from the chevron structure to the quasi-bookshelf structure[19] after cell training in an electric field. The electrical treatment was performed by applying 5 of minutes alternative voltages of rectangular waveform with an amplitude of 10 V and a frequency of 10 Hz. The resultant quasi-bookshelf structure is shown in Fig. 3.

3.2 Electro-optic performance

Figure 4 shows the electro-optical response of FLC cells for a rectangular driving signal with an amplitude of 5 V and period of 1 msec. This cell was not preliminarily treated with an electric field. There is evidence that the switching time is less than 200 µsec. The treated cell shows a similar response.

In the next stage, the electro-optical response of FLC cells for a bipolar driving pulse with an amplitude of 20 V and duration time of 1 msec was measured. Figure 5 illustrates the response for a cell previously electrically treated. The contrast due to bistable switching is higher than 350:1 for a 650-nm wavelength. Because mechanical contact with the alignment substrate is avoided, this method is especially attractive for FLC displays on an ALCOS base, particularly used in mobile phones, PDAs, and e-books. Due to the new alignment procedure, in addition to high resolution, fast switching, and low energy consumption, these displays acquire high electro-optic contrast. The electro-optic contrast of the chevron texture is considerably lower (80:1) because the C1 structure has a much smaller switching cone angle than an optimal 45°.

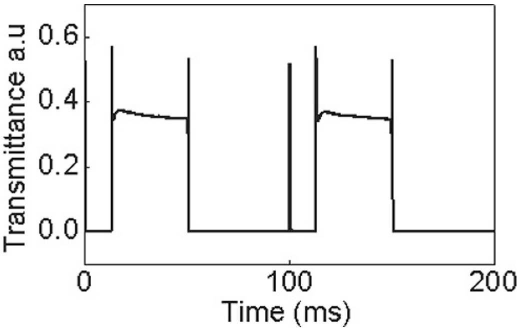

FIGURE 5 — Optical response of the electrically treated FLC cell on the bipolar rectangular driving pulse with an amplitude of 20 V and duration time of 1 msec. Switching contrast is higher than 350:1.

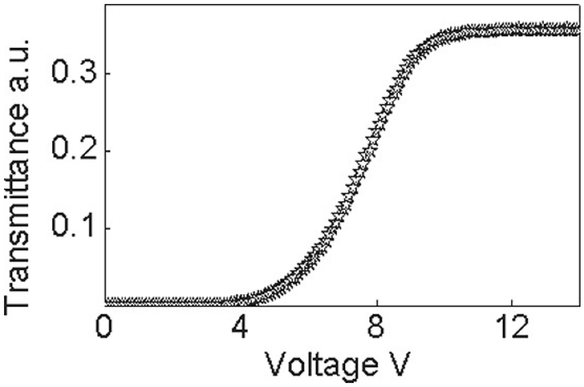

FIGURE 6 — Transmission–voltage characteristics (TVC) dependence of FLC cell aligned by plasma-beam etching process.

Finally, Fig. 6 shows the transmittance–voltage characteristics (TVC) dependence of FLC test cells measured by varying the amplitude of the bipolar driving pulse in the range 0–14 V. There is evidence that a sufficient amount of gray levels can be generated and stabilized. This opens perspectives for plasma-beam alignment for full-color displays, especially for those based on the color-sequential principle.

3.3 Nanotopology of alignment films

Figures 7 and 8 present atomic-force-microscopy (AFM) images and corresponding Fourier transformations for the unprocessed and plasma-beam-processed substrate. There is evidence that unprocessed PI films have moderate roughness and isotropic topology. Plasma treatment strengthens

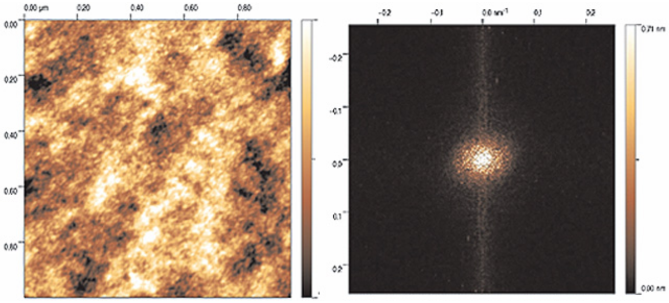

FIGURE 7 — (a) 2-D atomic force microscopy (AFM) image and (b) its Fourier transformation for the unprocessed polyimide film.

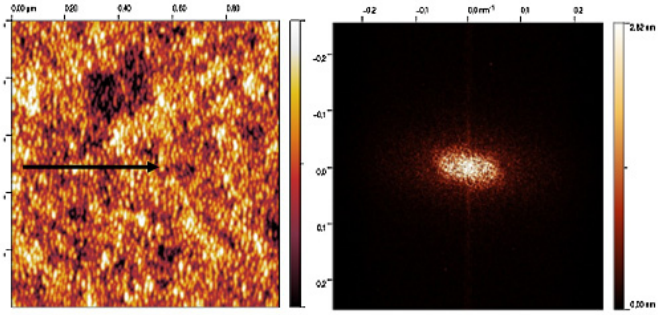

FIGURE 8 — (a) 2-D atomic force microscopy (AFM) image and (b) its Fourier transformation for the polyimide film obliquely processed by a plasma beam during 20 min. The arrow in (a) marks the surface projection of the plasma beam.

surface roughness and induces relief anisotropy. The direction of minimal roughness was either in the direction of surface beam projection (low exposure doses) or in the perpendicular direction (higher doses). In the latter case, anisotropy of surface relief is especially pronounced (Fig. 8); a ripple structure arises similar to that which is usually formed on the surface of inorganic films.[20] As we checked,[12,13] conventional *nematic* LC align in the direction of minimal roughness, *i.e.*, in full accordance with the Berreman rule.[21]

In the past several years, efforts were made to find the correlation between the morphology of SiO_x aligning films and FLC alignment. According to Ref. 7, an increase in the roughness of these films improves FLC alignment eliminating zigzag defects. In full agreement with this result, FLC alignment in our tests improved with an increasing dose of plasma-beam treatment (*i.e.*, with an increase in roughness). The roughness anisotropy also seems to be an important factor in the alignment quality of FLC, similarly to nematic LC.[12]

4 Conclusions

In conclusion, plasma-beam-deposited substrates yield highly uniform and defect-free alignment of ferroelectric liquid crystals. Due to this FLC, cells show high electro-optic contrast. Besides, they demonstrate fast switching and stable gray scale. This leads to perspectives for this alignment method in a number of known display applications of FLC, such as e-paper, small displays for mobile phones and PDAs, and color TV LCDs. As we believe, good alignment characteristics obtained by using the anode-layer-source process are common for anisotropic etching processes, *e.g.*, those based on ion beams from the Kaufman source.[11] According to our results, alignment characteristics of FLC are rather sensitive to the surface topology of the alignment films: FLC alignment improves with increasing roughness amplitude and roughness anisotropy grows with the dose of plasma-beam treatment.

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