IPS-LCD Using a Glass Substrate and an Anisotropic Polymer Film

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***Abstract*—A lightweight in-plane-switching liquid crystal display (IPS-LCD) using a single glass substrate and an anisotropic polymeric film is demonstrated. The liquid crystal molecules are aligned by the elongated polymer grain of the film. The alignment capability of the anisotropic film is comparable to a buffed polyimide layer. Compared to the LCD using two glass substrates, our new device exhibits a comparable contrast ratio (∼514:1), driving voltage, and response time because of good LC alignment. Such an anisotropic film can also function as a phase compensation film for widening the viewing angle. This technology is particularly attractive for making single-substrate displays and also has potential for a double-layered guest-host display and a flexible display using IPS LCDs.**

***Index Terms*—Anisotropic polymer film, in-plane switching, single-substrate liquid crystal display (LCD).**

I. Introduction

MOST liquid crystal display (LCD) devices use two glass substrates in order to confine the fluidic liquid crystal (LC). To align the LC molecules, the inner surfaces of the substrates are usually coated with a thin polyimide (PI) layer. These PI layers are mechanically buffed to produce uniform pretilt angle. To reduce weight, the single glass or plastic substrate approach has been explored recently in which the LC device consists of a glass substrate and a thin polymer film. Although the polymer film does not have electrode, it can still be used in the in-plane-switching (IPS) mode where the striped electrodes are located on the bottom glass substrate.

IPS LCD is an important technology for achieving wide-viewing angle. The typical IPS LCD consists of two glass substrate with rubbed polyimide. One of the substrates has electrode stripes in order to provide in-plane electric fields. In the voltage-off state, the LC directors are parallel to the striped electrodes. As the voltage exceeds a threshold, the LC directors are rotated by the in-plane electric field. In order to reduce the weight of an IPS LCD which has two glass substrates, several display manufacturers are using thinner glass substrates. However, to prevent the breaking of the thin glass substrates the cost and assembly processes are relatively complicated. By replacing a glass substrate with a polymer film, a single glass substrate IPS LCD is a promising approach for reducing the weight of LCDs.

Several of such single-substrate IPS-LCDs have been demonstrated. Penterman *et al.* [1]–[3] proposed the photo-enforced stratification (PES) method where the polymer walls and a cover substrate are formed after photo-induced phase separation processes. Kim *et al.* [4] proposed single substrate devices by using phase separated composite film (PSCOF) as a cover substrate. But in both methods the top polymer film does not have capability to align the LC molecules and the polymer walls can cause light scattering. The polymeric film without alignment capability would reduce the device contrast ratio and lengthen the response time because of its weak anchoring strength. To overcome these drawbacks, some research groups proposed thin aligned-polymer film method. Sato *et al.* [5] developed a fluorinated polymer film for aligning LC on plastic substrates, however, it still requires rubbing process. Murashige *et al.* [6] demonstrated a molecule-aligned LC polymer film. The film was coated on the surface of a rubbed polyimide substrate. A partial photo-polymerization process was required in order to achieve uniform alignment within the film. The anchoring strength of the film is about one order of magnitude weaker than that of the buffed polyimide. The method used to align the LC molecules near the top polymer film of the single-substrate LCD remains an urgent technical challenge.

In this paper, we developed new processes for making an anisotropic polymer film. We also demonstrate a single- substrate IPS LCD using an anisotropic polymer film as the top substrate. The performances, such as contrast ratio, driving voltage, and response time, are comparable to the two-glass- substrate IPS LCDs. The function of this polymer film is versatile. It not only serves as a top substrate but also aligns the LC molecules without any rubbing treatment. Furthermore, by controlling the fabrication process the polymeric film can also function as a phase compensation film. This technology can be extended for making high-contrast double-layered guest-host displays and flexible displays using IPS LCDs.

II. Experiment

The materials we used for fabricating the aligned-polymer film are a Merck E7 nematic LC mixture, photo-initiator IRG184, and an LC monomer RM-257 (4-(3-Acryloyloxy-propyloxy)- benzoic acid 2-methyl-1,4-phenylene ester) mixture. The concentration of IRG184 is 1 wt%. Fig. 1 plots the phase diagram of the LC/monomer mixture at various concentrations before UV curing. The LC/ monomer mixture was

Manuscript received November 2, 2005; revised December 6, 2005. This work was supported by Toppoly Optoelectronics (Taiwan), Chu-Nan, Taiwan, R.O.C.

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Digital Object Identifier 10.1109/JDT.2005.863777

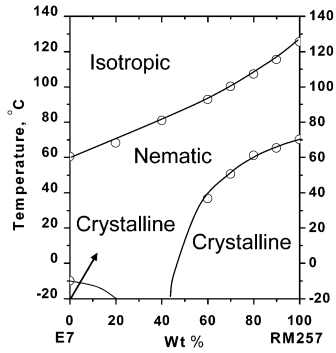

Fig. 1. Phase diagram of the E7/RM257 mixtures. All the mixtures have 1 wt% IRG184 photo-initiator.

injected into a homogeneous cell with 12 μm gap and then the cell was exposed to a ultraviolet (UV) light with intensity $I = 10$ mW/cm^2 for ~ 30 min at a constant temperature. After UV exposure, the two substrates of the homogeneous cell were peeled off and a stratified anisotropic film with 12 μm thickness was obtained. Based on our experiment, at a fixed curing temperature the anisotropic polymer film is more flexible if the monomer concentration is lower. When the monomer concentration is between 70wt% and 100 wt%, the anisotropic polymer film can align LC molecules as long as the UV curing temperature is within the nematic phase. In the isotropic phase, the film's alignment capability is rather weak. Curing temperature also influences film's flexibility. In the rest of this paper, the aligned-polymer film used consists of E7, IRG184, and RM257 at 9:1:90 wt% ratios and the UV curing temperature is 90 °C. The LC/monomer mixture has a nematic phase between 65.3 °C and 115.5 °C before UV curing.

The detailed cell structure is depicted in Fig. 2. Our LC cell consists of a top anisotropic polymer film and a bottom IPS glass substrate. An IPS glass substrate which was overcoated with a thin polyimide layer and then mechanically buffed was used as the bottom substrate. The electrode width is $W = 4$ μm and the electrode gap is $G \sim 10$ μm. The rubbing direction of the glass substrate is 10° with respect to the electrode stripes. The cell gap between the anisotropic polymeric film and the IPS substrate is $d = 12$ μm. The orientation of the LC directors within the anisotropic film was anti-parallel to the rubbing direction of the IPS substrate. The LC mixture employed for the IPS cell is also E7. The uniformity of the cell gap is not an issue because the film is laminated on a sheet polarizer. We used one-drop filling method to fill the LC cell. The sample size of the IPS cell is around 25 mm by 25 mm.

To further observe the surface morphologies of the anisotropic polymer film, an atomic force microscope (AFM) (Dimension 3100, Digital Instruments) was used to image the rubbed polyimide surface and anisotropic polymer film surface as shown in Fig. 3. Silicon nitride cantilever with a normal spring constant of 30 N/m and an apical radius of 20 nm was used. The AFM measurements were performed in tapping mode at a scan rate of 1 Hz in air under ambient conditions. In Fig. 3(a) and (b), the anisotropic polymer film is rougher than the rubbed PI film whose thickness is ~ 100 nm. In Fig. 3(b), the surface of the anisotropic polymer film shows elongated

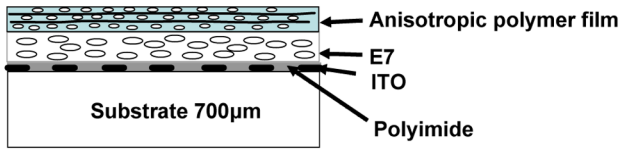

Fig. 2. Device structure of an IPS LC cell consisting of a top anisotropic polymeric film and a bottom ITO-glass substrate. The thickness of the top anisotropic film is 12 μm, and the cell gap is also 12 μm. (Color version available online at http://ieeexplore.ieee.org.)

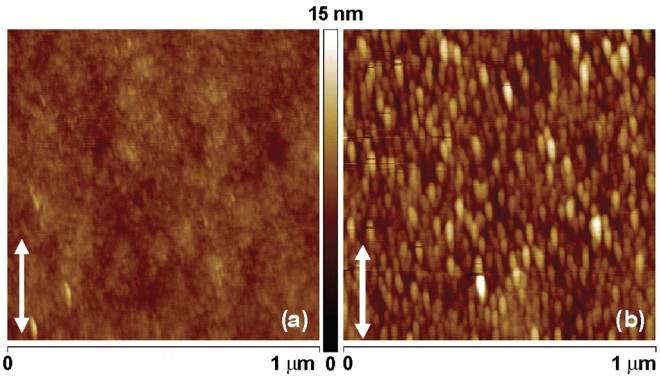

Fig. 3. AFM images of: (a) the rubbed PI film surface and (b) the anisotropic polymer film surface. The LC directors are aligned along the arrow. The color bars indicate the height. (Color version available online at http://ieeexplore.ieee.org.)

aggregation of polymer grains along the arrow direction. The rms roughness of the surface can be defined as rms average of height deviations taken from the mean data plane. Then, the rms roughness of the surface of the anisotropic polymer film is 1.52 nm. The LC molecules tend to align along the direction of the elongated polymer grains in order to minimize free energy.

The physical mechanism of how the anisotropic film aligns the LC molecules is not yet completely understood. A speculated mechanism is due to the nano-structure of the elongated polymer grain. Before photo-polymerization, the LC molecules and LC monomers are aligned by the rubbed PI layers. After phase separation, the polymer grain of the polymeric film aggregates and elongates along the rubbing direction. During fabrication process, when we peel off the polymer film from the ITO glass substrates the LC molecules near the surface stay on the glass substrates which leave the anisotropic polymer film with valleys and polymer network structures. When the polymeric film is used as a top substrate, the injected LC tends to fill the valleys and follow the elongated polymer grain direction. The film seems to have memory effect before it is peeled off from the PI cell. The size and the structure of the polymer grains depend on the fabrication conditions. These factors will undoubtedly affect the anchoring strength and the molecular alignment of the IPS cell.

III. Results and Disscussions

Fig. 4(a) shows the microscope photos of the single-substrate IPS cell covered by the top anisotropic polymer film under crossed-polarizers at $V = 0$, and 10 V_{rms}. A white light was used for taking the microscope photos. The optical axis of the

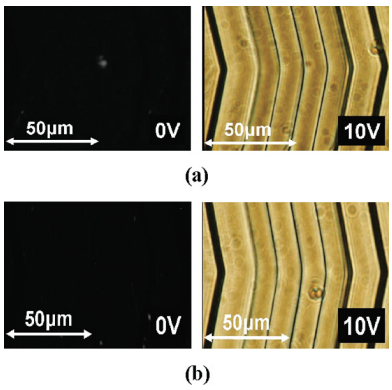

Fig. 4. Microscopic photos taken from a polarizing microscope at different voltages with crossed polarizers. (a) Our anisotropic film-glass IPS cell and (b) the conventional IPS cell. The two black zigzags in the photos are TFT source lines. (Color version available online at http://ieeexplore.ieee.org.)

bottom polarizer was oriented parallel to the LC rubbing direction. At $V = 0$, a very good dark state is achieved indicating that the LC directors are well aligned. The threshold voltage of the cell is $V_{\rm th} \sim 2\ {\rm V_{rms}}$ which corresponds to $E = 0.2\ {\rm V}/\mu{\rm m}$ (note that $G = 10\ \mu$m). As the voltage exceeds $V_{\rm th}$, the transmittance increases gradually because the LC directors begin to follow the external electric field. For comparison, a conventional IPS cell was also prepared, i.e., the bottom glass substrate has interdigitated ITO electrodes and the top substrate is a plane glass with rubbed polyimide. The rubbing direction of the top substrate is anti-parallel to the bottom IPS substrate. Fig. 4(b) shows the microscopic textures of the conventional IPS cell. Compared with Fig. 4(a) and (b), our single-substrate IPS cell has very similar dark and bright states to the conventional IPS cell. This indicates that our anisotropic polymer film exhibits an excellent alignment capability. The contrast ratio can be measured quantitatively from Fig. 5.

Fig. 5 compares the voltage-dependent transmittance (VT) of the single-substrate IPS cell (black line) with the conventional IPS cell (gray line). To measure the VT curves, the cells were sitting between two crossed polarizers. A standard white light was used in this experiment. The transmittance of these two curves overlaps quite well. The saturation voltage is $\sim 20\ {\rm V_{rms}}$ for both cells. The contrast ratio (CR) is defined as the ratio of the maximum transmittance to the minimum transmittance. The contrast ratio of our single-glass-substrate IPS cell was measured to be 514:1 which is comparable to the conventional IPS cell. Our single-substrate IPS cell exhibits a much higher contrast ratio than all previously reported structures in the same category [1]–[4] because the anisotropic film we developed, indeed, has a very good alignment capability.

In addition to enhancing contrast ratio, the anisotropic film also contributes to the fast response time because of its strong anchoring energy (similar to that of the buffed PI film). We measured the rise and decay times of our single-glass-substrate IPS cell and compared results with the conventional IPS cell. Results are shown in Fig. 6. At $V = 20\ {\rm V_{rms}}$, the measured rise and decay times are 8 and 63 ms for our glass-film IPS cell and 7 and 69 ms for the conventional IPS cell. The comparable response times of both cells indicates that our anisotropic film has

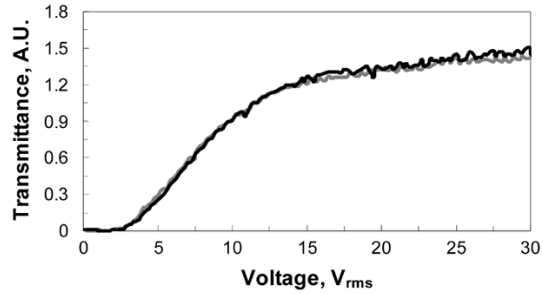

Fig. 5. Voltage-dependent transmittance of our anisotropic-film-glass IPS cell (black line) and the conventional IPS cell (gray line).

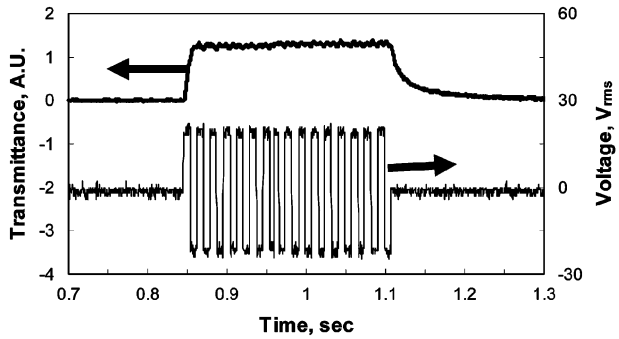

Fig. 6. The measured response time of our film-glass IPS cell. The rise time is ~ 8 ms and decay time ~ 63 ms. Cell gap $d \sim 12\ \mu$m.

a similar anchoring strength as the buffed PI alignment layer. The observed slow decay time in both cells is due to: 1) the thick LC layer ($d \sim 12\ \mu$m) employed and 2) the relatively high viscosity of the E7 LC mixture. For a practical IPS LCD, the cell gap is $\sim 5\ \mu$m and the LC viscosity is low. Under such a circumstance, the decay time should be reduced to ~ 12 ms and voltage dropped to $\sim 5\ {\rm V_{rms}}$. It is known that E7 is not a TFT-grade LC. The reason we used E7 is simply because it is available in our laboratory.

The anisotropic polymer film we fabricated has birefringence $\Delta n \sim 0.1$ at $\lambda = 633$ nm. Since the device is operated in IPS mode and the polarizer is parallel to the anisotropic direction of the film, the Δn of the film does not affect the EO properties. For a practical display, the birefringence of the anisotropic film can be an advantage for compensating the light leakage of the crossed-polarizers in the IPS mode [7]. By controlling the fabrication process, such as the UV curing temperature, the polymer film can be made either anisotropic or isotropic depending on the applications. Thus, this type of film can be used as a phase compensation film besides the IPS LCD. In general, the birefringence of a LC or LC polymer decreases as the temperature increases [8], [9]. As shown in Fig. 1, the E7/RM257 mixture exhibits a nematic phase between 65.3 °C and 115.5 °C. Thus, within this range if the UV curing temperature increases, then the film's birefringence would decrease. If the UV curing temperature is higher than 115.5 °C (the clearing temperature of LC/RM257), the polymer film would become isotropic. Moreover, the flexibility of the film can be controlled by changing the concentration of RM257. The film is more flexible as the concentration of RM257 decreases. Substrate flexibility is one of the critical issues for flexible displays.

The ambient temperature can affect the LC alignment because of the thermal expansion of the elongated polymer film. However, our LC device is operated at room temperature, so the film still has good alignment capability.

With molecular alignment capability, the anisotropic film enables other LC operation modes to be considered for display applications. For example, the twist type IPS cell can be considered by using an IPS glass substrate and our anisotropic film whose alignment direction is orthogonal to the bottom substrate. Such as an anisotropic polymer film can also be used for a double-layered guest–host (GH) display [10] or a double-layered LC phase modulator [11]. Although some research groups [12]–[14] proposed crossed-stacked GH LCD using either PI-coated glass substrate or a mylar film as a cell separator. The parallax problem is unavoidable because of the extra glass substrate. The mylar film cannot align LC molecules because its glassy temperature is lower than the baking temperature of polyimide. Without alignment, the contrast ratio is greatly sacrificed. The middle cell separator of the double cell GH LCD can be replaced by our anisotropic polymer film which not only reduces the parallax but also increases the contrast ratio. A tradeoff is the increased driving voltage because the polymer film shields the applied voltage.

IV. Conclusion

We have demonstrated a lightweight single-glass-substrate IPS LCD using an anisotropic polymer film. The anisotropic polymer film has the comparable alignment capability to the rubbed PI film. As a result, similar contrast ratio, response time, and voltage-dependent transmittance to a conventional IPS cell employing two glass substrates are obtained. The LC molecules are aligned by the elongated polymer grains. Besides, the polymeric film is birefringent which can be also used as a phase compensation film for improving the viewing angle of the IPS LCD. Although there are some technical difficulties for making large-sized and uniform anisotropic polymer film, potential applications of such an anisotropic film for a double-layered GH display and flexible display are still foreseeable.

Acknowledgment

The authors would like to thank C. Mei Optoelectronics (Taiwan, R.O.C.) for providing the ITO glass substrates.

References

[1] R. Penterman, S. I. Klink, H. D. Koning, G. Nisato, and D. J. Broer, "Single-substrate liquid crystal displays by photo-enforced stratification," *Nature*, vol. 417, pp. 55–58, May 2002.
[2] P. Raynes, "Liquid crystal painting," *Nature*, vol. 417, pp. 28–29, May 2002.
[3] J. P. A. Vogels, S. I. Klink, R. Penterman, H. D. Koning, E. E. A. Huitema, and D. J. Broer, "Robust flexible LCDs with paintable technology," in *Soc. Inform. Display Tech. Dig.*, vol. 35, May 2004, pp. 767–769.
[4] I. Kim, J. H. Kim, D. Kang, D. M. Agra-Kooijman, and S. Kumar, "Fabrication of electro-optic devices using liquid crystals with a single glass substrate," *J. Appl. Phys.*, vol. 92, pp. 7699–7701, Dec. 2002.
[5] H. Sato, H. Fujikake, H. Kikuchi, Y. Iino, M. Kawakita, and Y. Tsuchiya, "Fluorinated polymer alignment layers formed at low temperature for plastic-substrate based liquid crystal devices," *Jpn. J. Appl. Phys.*, vol. 40, pp. L53–L55, Jan. 2001.
[6] T. Murashige, H. Fujikake, S. Ikehata, and F. Sato, "Anchoring strength of thin aligned-polymer films formed by liquid crystalline monomer," *Jpn. J. Appl. Phys.*, vol. 42, pp. 1614–1617, Apr. 2003.
[7] R. Lu, X. Zhu, Q. Hong, and S. T. Wu, "Ultrawide-view liquid crystal displays," *J. Display Technol.*, vol. 1, no. 1, pp. 1–14, Sep. 2005.
[8] S. T. Wu, "Birefringence dispersion of liquid crystals," *Phys. Rev. A*, vol. 33, pp. 1270–1274, Feb. 1986.
[9] J. Li, C. H. Wen, S. Gauza, R. Lu, and S. T. Wu, "Refractive indices of liquid crystals for display applications," *J. Display Technol.*, vol. 1, no. 1, pp. 51–61, Sep. 2005.
[10] S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays*. New York: Wiley, 2001.
[11] Y. H. Lin, H. Ren, Y. H. Wu, Y. Zhao, J. Fang, Z. Ge, and S. T. Wu, "Polarization-independent phase modulator using a thin polymer-separated double-layered structure," *Opt. Exp.*, vol. 13, pp. 8746–8752, Oct. 2005.
[12] T. Uchida, H. Seki, C. Shishido, and M. Wada, "Bright dichroic guest-host LCDs without a polarizer," in *Proc. Soc. Inf. Display*, vol. 22, Jan. 1981, pp. 41–46.
[13] M. Hasegawa, K. Takeda, Y. Sakaguchi, J. Egelhaaf, E. Lueder, Y. Taira, and A. C. Lowe, "320-dpi 4-inch reflective stacked crossed guest-host display," in *SID Symp. Dig.*, vol. 30, May 1999, pp. 962–965.
[14] M. Hasegawa, C. Hellermark, A. Nishikai, Y. Taira, and A. C. Lowe, "Reflective stacked crossed guest-host display with a planarized inner diffuser," in *SID Symp. Dig.*, vol. 31, May 2000, pp. 128–131.

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