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## Flexible Liquid Crystal Cells without Alignment Film

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*By generating microgroove pattern on the plastic substrate, liquid crystals (LCs) are aligned on the flexible substrates immediately without coating alignment polymer. This flexible LC cell proposed in this paper preserves comparable electro-optical properties while bending. The plastic film and the alignment layer integrated into an alignment substrate could prevent cracks of the additional polymer alignment layer during the bending condition. This method holds promises to be applicable to the roll-to-roll process to increase efficiency of the production.*

**Keywords:** flexible LCD; LC alignment; nanoimprint lithography

### I. INTRODUCTION

Many flexible displays based on plastic substrates have been designed and developed in recent years. They are taken to be the mainstream displays for next generation displays. The applications range from hand-held electronic products such as smart cards, electronic books, watches to wearable displays, image-rendering wall hangings, etc. Compared with traditional liquid crystal displays (LCDs) using glass substrates, these novel alternatives have attracted large attention due to several merits such as flexibility, light weight, thin profile, high shock resistance, and high portability. Among them, four leading

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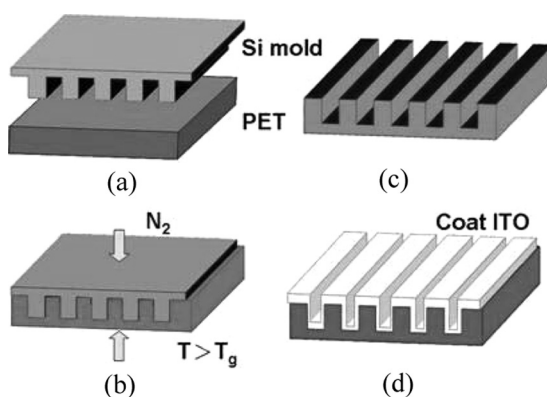
prototypes are E-ink [1], electrophoretic display (EPD) [2], organic light emitting diode display (OLED) [3], and LCDs [4–9]. E-ink has low power consumption and high contrast ratio, but it is not suitable for color displays. Comparing to the EPD, the LCD has faster response time and lower driving voltage to be a motion image display. Furthermore, the material of LCD has better stability and lower cost than that of OLED. Thus the applications of LCDs using plastic substrates are burgeoning nowadays. Even so, aligning LCs uniformly on plastic substrates is still a crucial issue investigated by many groups in the world [4–9]. In many flexible LCDs, for producing microgrooves, polymer films were still utilized to be coated on plastic substrates to be the alignment layers [4–7]. But the substrates coated with polymer alignment layers which would easily get ruptured during many bending times in practice. In addition, a high-temperature baking process (about 250°C) of forming a rigid alignment film is a serious problem causing thermal distortion for plastic substrates. Thus, a number of studies have been proposed that maintaining LC alignment can also be achieved via the formation of polymer networks [8–9]. However, residual polymers of unexposed region result in lower transmittance and higher operating voltage. Therefore, to make the flexible materials serve not only as substrates but also as alignment layers will be a very critical topic for the fabrication of flexible LCDs.

In this paper, we fabricate grating microgrooves directly on the surface of flexible substrates to align LCs immediately by using thermal nanoimprint lithography (thermal-NIL). Without coating the polymer alignment layers, the alignment-layer free substrates can avoid cracks of the traditional LC alignment layer during the bending process. The flexible LC device fabricated by this method is found to possess lower driving voltage and comparable response time compared to the traditional LCDs. Furthermore, our method suggests that one could fabricate multifunctional substrates for flexible LCDs without additional polymer alignment layers.

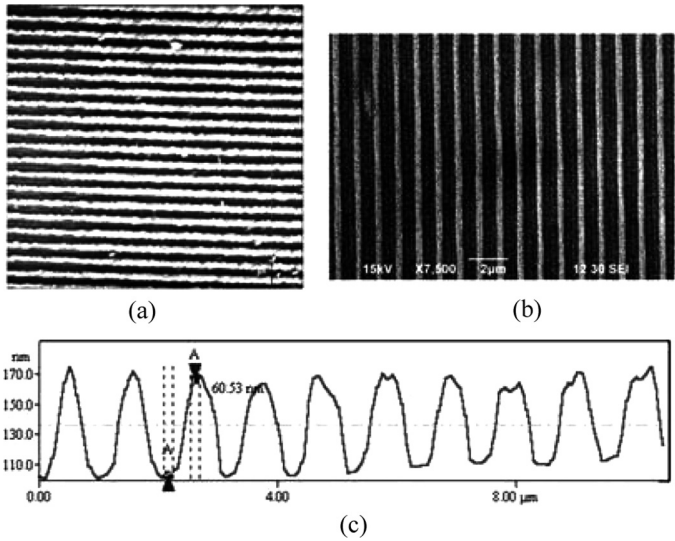
## II. EXPERIMENTAL DETAILS

The flexible substrate we choose in this study is polyethylene terephthalate (PET) film, which is a kind of transparent plastic with some good properties like high transmittance, low coefficient of thermal expansion, stable mechanical property, good chemical resistance, and so on. According to these advantages, PET films are used for touch panels widely. The surface of the PET substrate is required to be flat before NIL. After being cleaned mildly in ultrasonic with ethanol and deionized water, the PET film was dried out by nitrogen gas. Then the

plastic films were prepared completely for the next step, thermal-NIL. Figure 1 shows the flowchart for the thermal-NIL process. The mold for NIL in this study is the silicon wafer with microgrooves patterned by the traditional microlithography process. The PET film was placed on the silicon mold in the chamber and then they were pressed together at the pressure of about 260 psi when the chamber was heated slightly above the  $T_g$  ( $\sim 78^\circ\text{C}$ ) of PET. This thermal-NIL enables the pattern of the mold to be replicated onto the plastic film via controlling the system under the proper temperature and pressure. The microgroove nanostructures of the PET film after nanoimprinting were measured by atomic force microscope (AFM), as shown in Figure 2(a). Figure 2(b) shows the scanning electron microscope (SEM) image of the surface structure of the PET. The width of the groove is about 500 nm. To avoid the high working temperature over  $T_g$  of PET, we use RF magnetron sputter [10] to coat a thin indium tin oxide (ITO) layer as an electrode on the microgroove surface of the PET at room temperature. After coating the thin ITO layer, the depth of grooves is about 60 nm (see Fig. 2(c)), which is still good enough for LC molecules alignment. Two patterned PET substrates were arranged to be a flexible  $90^\circ$  TN cell. The cell gap of the LC cell is  $1.5\mu\text{m}$  and the LC material is a nematic LC (5CB,  $n_e = 1.736$ ,  $n_o = 1.5442$ ,  $\Delta\epsilon = 13.0$ ). After sealing the substrates by UV glue, the



**FIGURE 1** Thermal nanoimprint lithography (thermal-NIL) method: (a) Heating the chamber results in a molten surface on the PET substrate; (b) Press the mold and PET substrate together by high-pressure nitrogen gas; (c) Remove the mold and the bare PET with microgrooves was obtained; (d) Coat ITO thin film as an electrode on the PET substrate.



**FIGURE 2** Morphology of PET surface-relief grating (grooves). (a) The AFM image of grooves; (b) This picture was taken by scanning electron microscope (SEM); (c) After coating an ITO film, the height of grooves measured by AFM was approximately 60 nm.

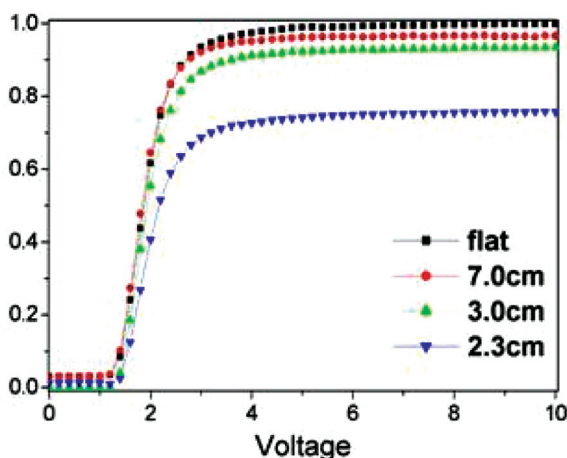
PET flexible substrates could still adhere to each other well against bending [11].

**III. ELECTRO-OPTICAL MEASUREMENT AND DISCUSSIONS**

By setting the polarizer and the analyzer to be crossed, the 90° TN cell is normally white as shown in Figure 3(a). Figure 3(b) shows the cell



**FIGURE 3** The 90° TN cell under crossed polarizers. LC molecules are aligned on the NTU-shaped pattern. (a) The 90° TN cell at the bright state with no applied voltage, and (b) With applied voltage about 3 volts, the TN cell is at dark state due to LCs align vertically with applied electric field.



**FIGURE 4** Electro-optical switching curves of our flexible TN LC cell under four different bending conditions. These TN LC cells are normally black with parallel polarizers. As the curvature increases, the transmittance of bright state gets lower. But even the curve radius is small as 2.3 cm, the transmittance still remains 70% of the flat one.

driven at 3 volt, the LCs are aligned vertically with applied electric field and thus make no phase retardation for the incident light. Under the crossed polarizers, the LC cell is at the dark state. In Figure 4, the electro-optical (EO) switching curve was measured under flat and three different bending conditions. These TN LC cells are set to be normally black under parallel polarizers. The transmissions of dark state under different bending conditions are almost the same. As the bending curvature increases, the bright state becomes worse. This could be resulted from the reduction of cell gap and certain disorder of LC molecules alignment when the LC cell is bent [12]. This problem could be overcome by forming the polymer wall to maintain the cell gap and confine LC molecules. However, even the curve radius is small as 2.3 cm, the transmittance still remains 70% of the flat one. Besides, the threshold voltage does not alter under flat and different bending conditions. The threshold voltages of these flexible LC cells without polymer alignment layers are around 1.2 volt, even lower than that of the traditional LCDs. This effect may be caused by the absence of the polymer alignment layer and the larger pitch of NIL-grooves than that of conventional rubbing [13]. When the applying voltage is 10 volt, the response time is measured around 13 ~ 15 ms, which is fast enough for a motion image display (see Table 1). The optical performances of

**TABLE 1** Threshold voltage and response time at different bending radius

Bending radius (cm)	Threshold voltage (V)	Response time (ms)
Flat	1.2	13.1
7 cm	1.2	15.3
3 cm	1.2	15.1
2.3 cm	1.2	13.2

these flexible TN LC cells are comparable to that of the traditional LC cells using glass substrates.

IV. CONCLUSIONS

By means of thermal-NIL technique, the microgroove pattern can be directly transferred on the plastic substrate, and thus LC molecules can be aligned immediately on the patterned flexible substrates without the need to have additional polymer coating layers for LC alignment. This method not only can avoid the cracks of the traditional alignment layer during bending process, but also increase the flexibility of rollable LC cells. The flexible TN LC cell of this design has the lower threshold voltage and comparable response time compared to the traditional LCDs. Moreover, when this flexible LC cell is bent, its threshold voltage and response time still remain the same. Finally, when the surprising conductive plastic material becomes more mature and more obtainable, the substrate, alignment layer, and the electrode could be combined into one. These non-laminated devices will raise the stability and the flexibility of the flexible LCD to be more practical rollable displays.

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