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A tactile sensing array with tunable sensing ranges using liquid crystal and carbon nanotubes composites

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ABSTRACT

This work presents the development of a novel 4 × 4 pressure sensing array with tunable sensing ranges. Carbon nanotubes (CNTs) dispersed in nematic liquid crystals (LC) composite is employed as the resistive sensing material. The structure of the sensing element, in which the LC–CNT composite is sealed, consists of a deformable PDMS elastomeric structure, an indium tin oxide (ITO) glass substrate and an ITO PET film. The force sensing ranges can be tuned by varying frequency of the driving voltage supplied by the array scanning circuitry. This tunable capability can be employed for the applications which require different measurement ranges of forces, without the need of adjusting the dynamic ranges of the sensor readout circuitry. The characteristics of the devices are measured and the pressure images with tunable capability are successfully captured. The driving and scanning circuit for resistive sensing array is also designed and implemented.

1. Introduction

Tactile sensing arrays are essential for robots to detect physical contact with humans or environment. Many researches on sensor arrays for normal and shear force detection have been reported. The typical sensing mechanisms for tactile arrays include capacitive, resistive, piezoelectric, and optical. Lee et al. [1] proposed a capacitive three-axis force image sensor array with excellent spatial resolution. Thin metal films, which are patterned on flexible substrates (e.g., polydimethylsiloxane (PDMS)), serve as the sensing electrodes as well as array interconnects. In [2], tactile sensing arrays were realized by dispensing individual conductive polymer bumps on interdigital copper electrodes for effectively improving the electrical isolation between adjacent sensing elements. Yoo et al. [3] presented the studies of piezoelectric and dielectric properties of piezoelectric ceramics for pressure sensor applications. In [4], optical fibers were proposed as the building blocks for the sensing elements of pressure sensor arrays. In addition, many other research works have been focused on manufacturing techniques, reliability issues, or special sensing functionalities. For example, an innovative approach has been proposed to realize a highly twistable and reliable artificial skin by using spiral electrodes as sensing electrodes and scanning traces [5]. With the increased interest on humanoid robots, the development of tactile sensors covering the whole robot body becomes popular [6]. Chang et al. [7] developed a large-area flexible sensor using a screen printing technology with the thixotropy sol–gel materials to create microstructures on two polyimide (PI) sheets. Bao et al. [8] demonstrated flexible capacitive pressure sensors with excellent sensitivity and short response times that can be inexpensively fabricated over a large area by patterning thin films of a biocompatible PDMS polymer.

The study on carbon nanotubes (CNTs) dispersed in nematic liquid crystals (LC) has received attentions recently [9,10]. It has been observed that the LC media can be strongly anchored to the CNT surface [11,12]. Also, the orientational order of LC can be transmitted to CNTs, which in turn gives rise to a high level of nematic order in CNTs organization. The electrical state of the LC–CNT composite can be switched between insulating and conducting states by varying the molecular orientation of the LC and CNT entities with external electric fields [13–16]. Also, it has been observed that the conductivity of LC–CNT composites is dependent on certain physical parameters, such as the concentrations of CNTs [17], temperature [17,18], electric (and magnetic) field [19–21], and frequency [21,22].

In this work, by employing LC–CNT composite and micromachining techniques, we first report a tactile sensing array which possesses the capability of tunable sensing ranges [23]. The structure of the sensing element, in which the LC–CNT composite is sealed, consists of a deformable PDMS elastomeric structure, an indium tin oxide (ITO) glass substrate, and an ITO PET film. The 4 × 4 electrode patterns on the ITO film and ITO substrate are fabricated by using typical lithography and etching techniques. The force sensing ranges can be tuned by varying the driving frequency for LC–CNT composites. The corresponding driving and scanning

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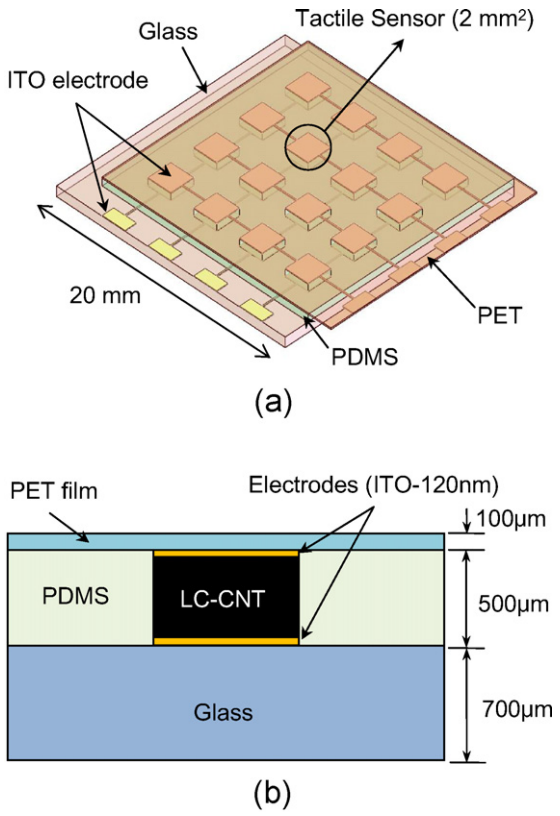

Fig. 1. (a) The schematic of the sensing array with tunable sensing range, (b) the detailed illustration and dimensions of the proposed tactile sensing element.

circuit is designed and developed. The characteristic of the sensing material and the performance of the sensing array will be measured and discussed. This paper is organized as follows: the design, principle and fabrication of the proposed sensing array are described in Sections 2 and 3. Measured results and discussions will be presented in Section 4. Finally, Section 5 draws the conclusions.

2. Operational principle and design

The frequency dependence of electrical conductivity for LC–CNT composites has been reported in [22]. The complex permittivity, which is shown in (1), can be employed to represent the associated capacitive effect (i.e., the real part, ε') and the conductive effect (i.e., the imaginary part, ε'').

$$\varepsilon = \varepsilon' + i\varepsilon'' \tag{1}$$

The frequency-dependent conductance can be determined by using the following formula:

$$\sigma(f) = 2\pi\varepsilon'' f^m \tag{2}$$

The value of m is dependent on CNT concentration and temperature. In general, m is determined by experiments, and is about from 0 to 0.35.

According to (2), higher driving frequency of LC–CNT composites induces higher conductivity (i.e., lower resistivity). In addition, similar to conductive polymers [24,25], LC–CNT composites also exhibit resistance change under external pressure forces. In this work, we utilize these behaviors to design and develop tactile sensing devices with tunable force sensing ranges. Fig. 1(a) shows the schematic of the proposed device. The upper and lower layers of the device are a PET film and a glass substrate, respectively. The PET film and the glass substrate are coated with ITO on one side. The deformable spacer layer is a PDMS polymer film. The sensing material is made by dispersing multi-walled CNTs (MWCNTs) in nematic liquid crystal (NLC) medium. The size of the 4×4 sensing array is 20 mm × 20 mm, and the size of each sensing element is 2 mm × 2 mm. The width of the metal trace between each element is 100 μm. Fig. 1(b) shows the cross-sectional view of an element. The LC–CNT mixtures are sandwiched between an ITO PET film and an ITO glass. The thicknesses of the PET film, the PDMS layer and the glass substrate are 100 μm, 500 μm and 700 μm, respectively.

3. Fabrication

3.1. LC–CNT composites

The liquid crystal (E7, Merck, Taiwan) used in this work has a nematic phase at room temperature, and its clearing point is 59.6 °C (i.e., *N–I* phase transition temperature, T_{NI}) Also, since E7 has a positive dielectric anisotropy, an external electric field will force the LC molecules to align in the direction of the field [12]. The MWCNTs used for this work are 10–20 nm in diameter and 1–2 μm in length with 95% purity (Golden Innovation Business Co., Ltd, Taiwan). The MWCNTs were doped at a fixed concentration of 0.5 wt% in the LC material (E7) and subjected to ultrasound at 40 kHz (400 W) with 70 °C for 5 h to reduce the CNTs bundling tendency. Finally, the mixture was degassed and the composite preparation was finished.

Note that CNT concentration strongly affects not only the conductivity of the composite, but also the dispersion of CNTs in LC. As the concentration of CNTs is lower than 0.1 wt%, the conductivity of the CNT–LC drops significantly [17]. On the other hand, a concentration higher than 1 wt% usually results in difficulty in obtaining a uniformly dispersed CNT suspension. Also, the supernatant after ultrasonic dispersion process is then collected and filtered using Whatman filters with 8 μm pore size. The resulting dispersion is quite stable, shows no signs of sediment in the course of months. Further details of this method can be found in Ref. [26]. In addition, the mixture was dispersed at a temperature above the T_{NI} of E7 for maintaining LC in isotropic phase and reducing the viscosity of liquid crystal.

3.2. Sensor array

Fig. 2 illustrates the fabrication process for the sensing array. Fig. 2(a) shows the fabrication processes for the upper and the lower electrode layers. The ITO glass and the ITO PET film, which are commercially available, were diced into smaller pieces of 20 mm × 20 mm. The samples were rinsed by isopropyl alcohol (IPA) and deionized (DI) water, and then were dried by nitrogen gas and dehydration baking on a hot plate at 90 °C for 15 min. Then, the ITO electrode structures on the PET film were patterned by oxalic acid [27] with photoresist as etching masks. The ITO film, which is about 120 nm in thickness, can be completely patterned with 0.3 M oxalic acid at 25 °C for about 10 min. Similar patterning process was also used to create the ITO electrode patterns on the glass substrate. Fig. 2(b) is the fabrication process of the PDMS structure layer. PDMS prepolymer and curing agent (Sylgard® 184 A and 184 B, Dow Corning) are mixed at a 10:1 ratio. After stirred thoroughly and degassed in a vacuum chamber, the prepared PDMS mixture was poured onto a patterned SU-8 master (GM 1070, Gersteltec Sarl). After cured at 90 °C for 60 min, the cured PDMS layer was peeled from the master substrate. Fig. 2(c) is the schematic of the assembled device. The lower ITO glass and the PDMS layer were bonded together after oxygen plasma treatment. Again, after oxygen plasma treatment on the top of the PDMS layer, the prepared LC–CNT composite was injected in the cell by a syringe, and then the upper ITO PET was bonded on the PDMS layer. The fabricated components and the assembled device are shown in Fig. 3. Fig. 3(a)