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A novel gas sensor using polymer-dispersed liquid crystal doped with carbon nanotubes

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ABSTRACT

This study presents the development of a novel chemical sensor that uses a sensing film consisting of a polymer-dispersed liquid crystal (PDLC) doped with carbon nanotubes (CNT) for acetone detection. The sensing element comprises a PDLC sensing film and planar interdigital electrode pairs. Chemical gas can be detected by measuring the changes in the electrical resistance of the sensing film caused by the orientational ordering transitions of the CNT and LC. The PDLC film in a rubbery state can be easily packaged and stabilized against mechanical shock. The devices can operate with a simple read-out circuit. The sensor gives a linear response for gas concentration from 100 to 1500 ppm, and the response time is less than 32 s. The influences of the film thickness and LC mixing ratio are also discussed.

1. Introduction

High sensitivity devices for detecting chemical and biological analytes are crucial for various applications, such as point-of-care (POC) diagnostics [1], micro total analysis systems (μTAS) [2], and chemical and biological warfare detection systems [3]. For practical applications outside laboratories, these devices must be portable and reliable. Recent studies have shown that nematic liquid crystal (LC) systems can be employed as reliable, low-cost, portable, and high-sensitivity sensors for chemical and biological agents [4,5]. The principles of the LC-based detection systems can be found in [6,7]. In general, the interfacial molecular events cause transitions in the orientational ordering of molecules within the LCs, which can be detected by monitoring the changes in the intensity of light transmitted through the LCs. In [8], the thin films of nematic LCs E7 supported on chemically functionalized surfaces for detecting several vapor phase organophosphorous nerve agents was proposed. Lindquist et al. [9] proposed a microelectroplated interdigital structure for LC-based chemical and biological sensors. The influence of bias voltage on transitions of molecular orientation in surface-driven LCs was studied for improving the sensitivity, response speed, and signal strength of LC-based sensors. In [10], the detection of organic vapor by cholesteric liquid crystals was demonstrated. Experimental results showed a red shift in the color that is reflected by cholesteric LCs when absorbing vapors. Jiang et al. [11] proposed a micropillar array that enables the formation of LC thin films, which can be used for gas-sensing applications. By using the microfabricated structure, thin LC films were stably and uniformly formed. Packaging liquid-state LCs on a miniaturized chip, with stability against gravitational forces and mechanical shocks is a vital issue, although it has not been universally resolved in the aforementioned works. In addition, the orientational transition of LC molecules can be easily observed by the unaided eye. However, bulky or expensive optical instruments are required to determine the magnitudes of the detected signals on LC films.

Because of outstanding thermal, mechanical, and electrical properties [12,13], carbon nanotubes (CNTs) have attracted considerable research interest for developing various applications during the past decade [14–16]. In addition, CNT-dispersed nematic liquid crystals (CNT-LCs) have drawn significant attention because of various interesting physical behaviors [17–19]. As CNT particles are dispersed throughout an LC matrix, an aligned ensemble of LC and CNT molecules can be obtained because an LC orientational order can be imposed on CNTs [20]. Moreover, CNT particles form conductive networks in CNT-LC materials, and the conductivity of a CNT-LC composite can be varied by changing the orientation of CNT-LCs. Therefore, it is possible to detect the concentrations of chemical and biological agents that change the orientation of LCs by measuring the conductivity of a CNT-LC material along a certain direction.

Recently, an approach based on polymer-dispersed liquid crystals (PDLCs) [21] has been proposed to avoid the flow of LCs, to enhance the mechanical stability, and to simplify the fabrication process. PDLCs are composite materials in which LC molecules are generally trapped in a transparent polymer medium, forming micrometer-scale LC droplets. Various applications for PDLC have

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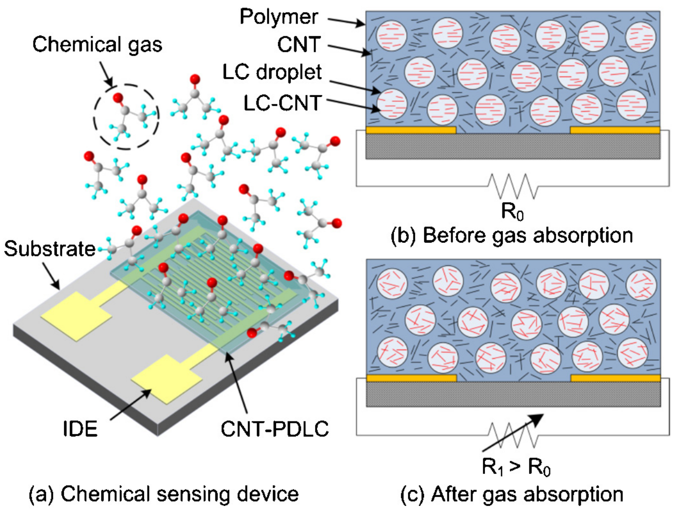

Fig. 1. Schematic diagram of (a) the CNT-PDLC chemical sensing device. (b) the random LC droplets in polymer and the orientation of CNT-LC (c) the sensor reactions when the CNT-PDLC material absorbs chemical gas. The CNT conducting networks of CNT-PDLC film are restructured.

been demonstrated. For example, a novel, self-adjusting smart window, based on light-controlled transmittance in a PDLC device, was proposed in [22]. Chen et al. [23] presented an artificial iris which consisted of PDLC rings for modulating ambient light intensity. In [24], a fiber-optic electric field sensor using a PDLC was reported.

In this work, a gas sensor design that uses a hybrid material of PDLCs and CNTs (CNT-PDLC) for detecting acetone gas was proposed. The sensing element comprises a CNT-PDLC sensing film and planar interdigital electrode pairs. The concentration of a chemical gas can be detected by measuring the electrical-resistance change of the sensing film because of the restructuring of CNT conductive networks caused by the transitions of LC orientational ordering. Compared to typical LC-based sensors, the proposed PDLC device is sufficiently durable to withstand gravitational forces and mechanical shocks. The sensing signals can be retrieved by using a simple readout circuitry. The PDLC film, which is a UV-curable acrylic-based polymer matrix, can be easily prepared using the polymerization-induced phase separation (PIPS) method.

2. Design and principle

Fig. 1(a) shows a schematic diagram of the proposed device. The CNT-PDLC thin film is coated on the interdigital electrodes (IDE). A gold interdigital electrode is patterned on a silicon substrate. Each IDE consists of 17 fingers. The dimensions of the finger are 2 mm × 60 μm, and the gap between each finger is 30 μm. Fig. 1(b) shows a schematic representation of the CNT orientation of the CNT-PDLC sensing film before chemical gas absorption. The orientations of CNTs and LC molecules are aligned to be parallel to the substrate because the LC media are normally strongly anchored to the CNT surface [20]. The initial resistance of the PDLC sensing element is indicated as R_0. The relationship between the anisotropy of surface conductivity and orientational order parameter of CNTs was presented in [25]. The work also indicated that conductivity anisotropy is dominated by the conducting path distributions along different directions in the material. Consequently, the concentrations of chemical or biological agents that change the orientation of LCs can be detected by measuring the conductivity of a CNT-LC material along a specific direction. Therefore, as shown in Fig. 1(c), the gas molecules diffuse through the CNT-PDLC film when the sensor is exposed to chemical gas, the chemical molecules will destroy the ordering of the LC phase, results in an isotropic liquid phase.

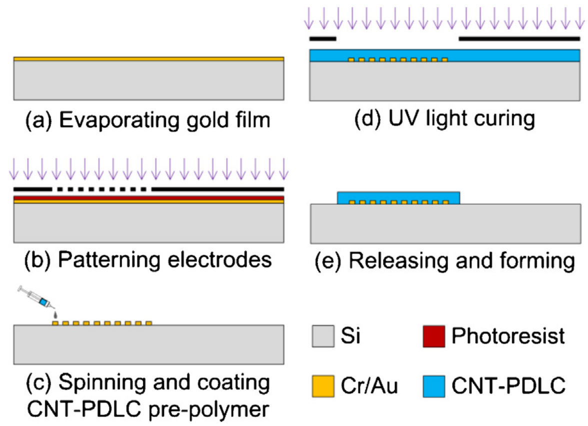

Fig. 2. Fabrication process of the CNT-PDLC chemical sensing device.

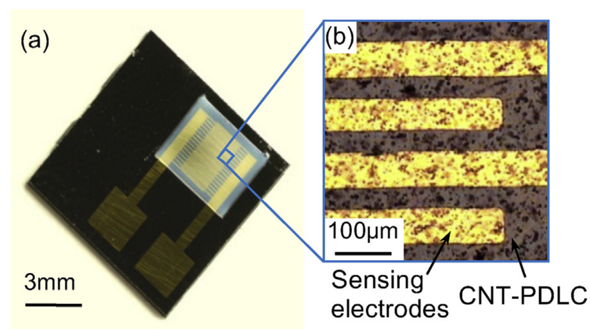

Fig. 3. (a) The fabricated sensor chip. (b) The optical image of the interdigital electrodes with CNT-PDLC.

After an orientational ordering transition within the CNTs and LCs, the CNT conducting networks in the PDLC are restructured, which in turn increases the resistance (R_1) of the polymer. In addition, PDLC is a composite material in which LC molecules are trapped in a polymer matrix, forming micrometer-scale liquid-state LC droplets. Unless the outer polymer structure is destroyed, the trapped liquid-state LC molecules are quite stable against mechanical shock. In addition, the inertia of the LC droplets (about 2–3 μm in diameter) is so small that gravitational force has very little influence on the trapped LC droplets.

3. Experiment details

3.1. Materials and fabrication

The fabrication process of the proposed device is shown in Fig. 2. The IDE pairs, which consisted of a 200 Å chromium and 3000 Å gold film, were fabricated on a silicon substrate by micromachining

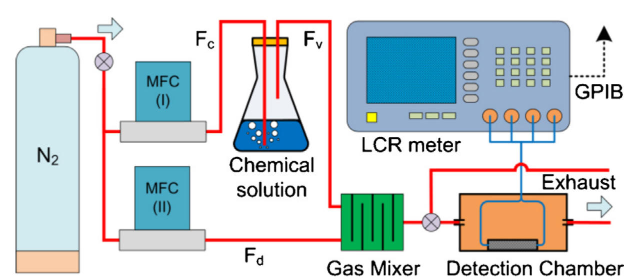

Fig. 4. Configuration of the experimental sensing apparatus. (F_c, The flow rate of the carrier gas; F_d, the flow rate of the dilution gas; F_v, the output flow rate of chemical vapor.)