Ultrathin CNTs Film Based on Marangoni Effect for Strain Sensing Application

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Abstract: The Marangoni effect has been applied in the preparation of large-area ultrathin films. However, defects occur frequently during the transfer progress of ultrathin films to substrates, which limits its application in scalable and massive fabrication. Carbon nanotubes (CNTs), as typical one-dimensional carbon materials, are widely used in wearable and flexible sensors due to their outstanding electrical and mechanical properties. In this paper, Marangoni-driven self-assembled CNTs film was obtained by injecting 0.5 mL 1 mg·mL−1 CNTs/ethanol dispersion on 100 cm² water dropwise; the thickness, sheet resistance, and optical transmittance (at 550 nm) of the as-prepared ultrathin film were 38 nm, 7.3 kΩ/□, and 66.9%, respectively. The CNTs film was transferred onto polydimethylsiloxane (PDMS) to prepare a conductive composite of CNTs/PDMS film and the sheet resistance of the composite film reached 21.0 kΩ/□. Furthermore, the packaged PDMS/CNTs/PDMS (PCP) strain sensors with a sandwich-like structure exhibited satisfactory sensitivity with a gauge factor of 3.4 at 50% strain, a large working range (89%), and excellent stability (>8000 cycles). The easy-making and low-cost sensors show great potential in wearable electronics, real-time motion detection, and electronic skin.

Keywords: carbon nanotubes; flexible strain sensor; Marangoni effect; ultrathin conductive film

1. Introduction

Strain sensors are devices that convert mechanical strain into electrical signals [1]. With the rapid development of electronic devices, flexible and stretchable strain sensors have acquired widespread attention among researchers. According to their signal transition mechanism, strain sensors can be generally divided into resistive [2,3], capacitive [4], piezoelectric [5,6], inductive [7], magnetic [8], and other types [9]. Among them, resistive-type sensors are widely favored because of their simple structures, wide working ranges, high sensitivity, stable signal output, and simple signal reception [2,3]. Typically, resistive-type sensors are composed of electrically conductive materials and flexible substrates. Conductive materials play an important role in constructing a conductive network and generating resistance change under strain. However, these conductive materials are difficult to use as strain sensors by themselves because of their tiny size and discontinuity [3]. The insulating flexible substrates not only show the function of supporting and connecting conductive materials, responding to stress and strain, but also make crucial contributions to the flexibility and stretchability of sensors. The cooperation of conductive materials and flexible substrates increases the working range and stability of sensors significantly [1,3]. The sensing mechanism of resistive-type flexible strain sensors is that the electron transport paths change due to the destruction and reconstruction of the conductive network under strains, or the contact resistance and tunneling resistance change due to the displacement of the conductive nanomaterials [2]. When the sensor is stressed, even minor strain will
lead to its electrical resistance changes and, after the stress is released, both the strain and resistance of the sensor will return to the initial status [1]. In addition, strain sensors can also be roughly classified according to their structures, such as full-filled [10,11], sandwich-like [12–14], and absorption-structured sensors [15–17]. A classical sandwich-like sensor can be fabricated by clamping the conductive film with two layers of flexible substrates. The sensors with a sandwich-like structure, owning high sensitivity and stability, have received extensive attention. As the “nerve endings” of the Internet of Things, the flexible strain sensors are the key components of smart devices and wearable electronics, which have a wide range of applications in human-computer interaction [18,19], electronic skin [20], health monitoring [21,22], and so on.

Carbon nanotubes (CNTs) have been widely used in flexible electronics due to their excellent electrical and mechanical properties [12,23,24]. CNTs can be fully mixed with liquid substrates to make conductive composite materials [25–27] or attached to flexible substrates by spray coating [13,28,29], blade coating [30], printing [31–33], swelling/permeating [34–36], layer-by-layer assembly [16,37,38], and other methods [14]. CNTs usually collaborate with other conductive materials, such as carbon black (CB) [38,39], graphene [16], and silver nanowires (AgNWs) [29], and the conductive network composed of the nano-materials of different dimensions can enable the sensor to exhibit a high sensitivity and wide working range simultaneously [37].

Generally, when CNTs sensors are stretched, the contact area between the conductive materials decreases and the tunneling distance increases, leading to an increase in resistance, which means that the sensor reflects its strain signal in the form of an electrical signal [13,40–42]. Chen et al. [13] prepared a stretchable sandwich-like strain sensor by a CNTs dispersion spray-coated to PDMS (0.16 mg/cm$^2$ CNTs in the conductive layer), which had a good optical transmittance of 53.1% at 550 nm and a wide sensing range of more than 130%. The sensor showed good stability and could monitor the subtle movements of facial expressions and human joint movements. Xue et al. [40] reported a method for preparing flexible strain sensors using ultrasonic technology, which induced physical effects, such as the cavitation effect and acoustic streaming to deposit CNTs onto the surface of PDMS. The sensor with green features exhibited a large stretchability (working range > 420%), high sensitivity (GF = 8.4–68.3), and excellent cyclic stability (>10,000 cycles at 50% strain). Mai et al. [41] adopted vacuum filtration to prepare the CNTs films (2.74–4.70 μm in thickness) on the polysiloxane substrates to fabricate stretchable conductive strain sensors. The strain sensor exhibited self-healing ability, self-adhesiveness, high sensitivity, linearity, low hysteresis, and long-term durability, with a gauge factor of 33.99 at 55% strain. Santos et al. [42] produced vertically aligned CNTs forests by chemical vapor deposition and then mechanically knocked down the aligned CNTs onto polyimide (PI) films to fabricate a flexible strain sensor. The results showed it was possible to quantify and indicate strain in three directions with only a small aligned CNTs patch.

However, the sensors based on CNTs have always been of great concern. A large amount of CNTs is often needed to meet the conductivity requirements, resulting in high manufacturing costs and complex processes for the sensors. Therefore, the simpler process and lower cost for conductive ultrathin CNTs films are crucial for the preparation and application of the sensors.

The preparation of ultrathin CNTs films by the Marangoni effect is one of the most convenient processes. When two liquids with different surface tensions meet, the surface tension gradient at the interface causes the liquid with the higher surface tension to flow to the one with the lower surface tension, which is called the Marangoni effect [43–45]. Ultrathin conductive films have been prepared and applied in flexible sensors by means of the Marangoni effect [46–50]. The films obtained by the Marangoni effect are usually a few layers thick of the raw materials [46,48], which greatly saves raw materials and makes the device transparent. The films can be transferred onto many kinds of flexible substrates to build the strain sensors, which usually have extremely high sensitivity under subtle strain but a limited working range [46,47,50]. Fortunately, the working range can be broadened by
adding a microstructure on the substrates or conductive layers [47], transferring conductive films repeatedly [44,49], and so on, although these steps will complicate the preparation process. In addition, the common methods associated with manual operation frequently result in the formation of cracks and bubbles in conductive films, which unavoidably affect the uniformity and conductivity of the ultrathin films. Thus, how to perfectly transfer ultrathin conductive films to flexible substrates to prepare the strain sensors is an attractive topic.

Herein, we report a facile and scalable fabrication method of the strain sensors with highly comprehensive properties based on the Marangoni-driven self-assembled CNTs films. The CNTs/ethanol dispersion was added onto the surface of deionized (DI) water dropwise, and then an ultrathin CNTs film was formed because of the Marangoni effect. A unique transfer method was proposed to transfer the CNTs films to the PDMS substrate multiple times without damage. It is proved that the sandwich-like PCP strain sensors possess satisfactory sensitivity, a broad working range, and excellent repeatability, which can be applied to human physiological signal detection.

2. Materials and Methods

2.1. Materials

CNTs (carbon purity: >99 wt%; diameter: 5–15 nm; length: 10–30 µm) were provided by Chengdu Organic Chemicals Co., Ltd. (Chengdu, China). PDMS (Sylgard 184 Silicone Elastomer) was purchased from Dow Corning. (Freeland, MI, USA). Ethanol (95%, analytical purity) was obtained from Tianjin Jiangtian Chemical Technology Co., Ltd. (Tianjin, China). Conductive silver paste was supplied by Shenzhen Wowesii Electronic Technology Co., Ltd. (Shenzhen, China).

2.2. Preparation of the Sensor

Fabrication of CNTs film. A certain volume of CNTs/ethanol dispersion (1 mg·mL⁻¹) was added dropwise onto the surface of 100 cm² DI water in a plastic square Petri dish, and an assembled CNTs film immediately formed on the DI water surface. The matching lid was put on the Petri dish closely and then the Petri dish was flipped carefully so that the CNTs film was transferred onto the lid. The interfacial assembly of CNTs film is demonstrated in Supporting Movie S1.

Fabrication of composite conductive film. Liquid PDMS and its curing agent were mixed at a mass ratio of 10:1. The mixture was placed into a vacuum drying oven for 0.5 h to remove the bubbles; thereafter, it was cast onto the dried CNTs film and spun at 300 r·min⁻¹ on the spin coater. After heating at 45 °C for 4 h, PDMS mixture was cured together with CNTs film. The obtained CNTs/PDMS film was turned over gently on the lid and we transferred another CNTs film onto a CNTs/PDMS film directly as mentioned above to increase electrical conductivity.

Fabrication of sandwich-like PCP strain sensors. Copper wires were drawn by conductive silver paste at both ends of the conductive layer to form electrodes. The width of the conductive layer was 0.8 cm and the distance between the two electrodes was about 2 cm. In the final step, an additional layer of PDMS was cured on the top of conductive film to protect the copper wire joints and form a sandwich-like structure. We call this resulting sensor a PCP strain sensor in this paper. For clarity, a schematic diagram for the fabrication procedures of the PCP strain sensor is presented in Figure 1.
2.3. Characterization and Measurement

The morphology of conductive films was characterized by field emission SEM (Regulus 8100, Hitachi, Tokyo, Japan) at an accelerating voltage of 3.0 kV. A thin layer of platinum was sputter-coated before SEM measurements. Sheet resistance of the samples was measured by a four-probe resistivity tester (RTS-8, Guangzhou Four Probe Technology Co., Ltd., Guangzhou, China). A UV-visible spectrophotometer (TU-1900, Beijing Purkinje General Instrument Co., Ltd., Beijing, China) was employed to measure the light transmittance of the samples over the range of 400–800 nm. The thickness of the ultrathin CNTs film was measured by an ellipsometer (M-2000v, J. A. Woollam Co., Inc., Lincoln, NE, USA). Raman spectrometer (inVia, Renishaw, Sheffield, UK) was employed to characterize the quality of CNTs composite film with 532 nm laser. The strain sensing behaviors of the PCP sensors were measured using an electrochemical workstation (VERTEX V16407, Ivium Technologies, Eindhoven, The Netherlands) coupled with a universal electronic tensile machine (WDW-05L, Jinan Spai Technology Co., Ltd., Jinan, China).

3. Results and Discussion

3.1. Self-Assembly Processes of Ultrathin CNTs Film

A certain volume of 1 mg·mL\(^{-1}\) CNTs/ethanol dispersion was injected onto the surface of DI water dropwise. The CNTs/ethanol dispersion diffused on the surface of the water rapidly, which motivated the CNTs to move and form a continuous film on the water instead of sinking into the water (as shown in Supporting Movie S1). As the volume of the injected dispersion increased, the tightness of the CNTs film gradually increased, which can be demonstrated by Figure 2a,e–i and Supporting Movie S1. The thickness of the CNTs film is not linearly related to the volume of the CNTs/ethanol dispersion. When the drop-on volume increased from 0.3 mL to 0.5 mL, the thickness of the CNTs film had grown from 21 nm to 38 nm, mainly due to the increased tightness between the CNTs. As the volume further increased to a critical point, the CNTs had completely covered the water surface and the compactness of the CNTs film was close to saturation. The surplus CNTs sunk to the bottom of the water so that the thickness of the CNTs film was almost unchanged. The CNTs films prepared with Marangoni self-assembly showed good optical transparency, as shown in Figure 2b. The optical transmittances at 500 nm of the films formed with 0.3 mL and 0.5 mL dispersion are 72.3%, 66.9%, respectively. Even with a maximum volume of 0.7 mL, the transmittance of the film can still reach 62.6%. In addition, this kind of self-assembly film has superior electrical conductivity. The sheet resistances of the CNTs films assembled by 0.3 mL and 0.5 mL dispersion are 13.9 kΩ/□ and 7.3 kΩ/□, respectively, as shown in Figure 2c.
Figure 2. (a) Relationship between thickness of CNTs films and volume of CNTs/ethanol dispersion injected. (b) Optical transmittance of different CNTs films based on PDMS. Inset is photograph of corresponding samples located on the logo of Tianjin University. (c) Sheet resistances of different conductive films. (d) Raman spectra of CNTs powder and 2 layers-combined CNTs composite film. SEM images of different CNTs films formed of (e) 0.3 mL, (f) 0.4 mL, (g) 0.5 mL, (h) 0.6 mL, and (i) 0.7 mL CNTs/ethanol dispersion based on polished silicon wafers, magnified 20 k. SEM images of different conductive films made of 0.5 mL CNTs/ethanol dispersion, belonging to (j) 1 layer-cured, (k) 1 layer-transferred, and (l) 2 layers-combined, magnified 50 k, respectively.

However, it remains a challenge to transfer ultrathin films on water to substrates perfectly. The skimming method generally used in the literature [46–49] relies heavily on manual operation. During the transfer process, the films are easy to crack or fold, affecting their whole electrical conductivity and limiting their scalable fabrication.

Herein, we designed an efficient transfer method that produces almost no defects. After the CNTs film was assembled on the water in a plastic square Petri dish, we covered...
the matching lid of the Petri dish tightly and flipped it over gently. As a result, the CNTs film was transferred from the water surface to the inside of the Petri dish lid. The ultrathin CNTs film was dried, whose sheet resistance was 7.3 kΩ/□ (“1 layer CNTs film” in Figure 2c). Then, the uncured PDMS mixture was poured onto the dried CNTs film, and the CNTs/PDMS composite film was obtained after curing, which we called a “1 layer-cured” film. In this case, the PDMS penetrated into the CNTs film deeply, limiting the overall conductivity compared with the pure CNTs film, as the insulating PDMS led to an increased tunneling distance [46]. For the ultrathin film formed with a 0.5 mL CNTs/ethanol dispersion, the sheet resistances of the CNTs film and the corresponding CNTs/PDMS film were 7.3 kΩ/□ and 196.3 kΩ/□, respectively, as shown in Figure 2c. For comparison, we transferred a layer of the CNTs film to the cured PDMS substrate directly to fabricate the conductive film, with the name of “1 layer-transferred” film, whose sheet resistance was 76.4 kΩ/□, indicating that its conductivity was much better than that of the film named “1 layer-cured” (196.3 kΩ/□) because the PDMS could not penetrate too much into the CNTs network while the CNTs film transferred onto the cured PDMS surface.

In order to improve the conductivity of the CNTs/PDMS composite films, the Marangoni-driven ultrathin CNTs films can be transferred repeatedly to the surface of the composite film. The sensors loaded with two layers of the CNTs film were named as “2 layers-combined” film, whose sheet resistance was 21.0 kΩ/□. It was confirmed by the Raman characterization in Figure 2d that the two layers-combined film was composed of a dense network of high-quality CNTs. The value of $I_D/I_G$ reflects the defect degree of the sample. The higher the value of $I_D/I_G$, the more defects the sample contains and the more irregular the structure. The $I_D/I_G$ values of the CNTs powder and two layers-combined film are 1.29 and 1.33, respectively, and the similar values mean a dense network of high-quality CNTs has been formed in the two layers-combined films [48].

From Figure 2c,j–l, we can see that the CNTs and PDMS were combined in different ways when we used different transfer steps, and the different penetration degrees of the PDMS and CNTs network led to the difference in the tunneling distances and electrical conductivity. In addition, the CNTs content is vital to the conductivity of composite films, including the dispersion volume used and the layer counts of the CNTs film attached to the substrate. The higher the CNTs content, the higher the conductivity of the composite film.

### 3.2. Electrical Behavior of PCP Strain Sensors

With the CNTs strain sensor being stretched gradually, the CNTs network is damaged to a certain extent, and the tunneling distance also increases, which results in an increase in resistance [46]. As demonstrated in Figure 3a–c, the working range and gauge factor (GF) of the PCP strain sensors obtained by the Marangoni-driven self-assembly of the different volumes of the CNTs/ethanol dispersion are significantly different. The CNTs are one-dimensional materials in a curly state [19]. The composite conductive film was composed of the CNTs network and PDMS. When the film was stretched to a small strain, the CNTs were gradually stretched, resulting in resistance change. When large strains occurred, the entangled CNTs slipped among the tubes and even cracked, leading to a further increase in resistance. We defined the strain when the sensitivity of the sensor increased sharply and the instability increased as the working range of the sensor. The GF was calculated to assess the sensitivity of the sensor, which is defined as $(\Delta R/R_0)/\varepsilon$, where $R_0$ (Ω), $\Delta R$ (Ω), and $\varepsilon$ (%) represent the initial resistance without strain, resistance change with strain, and applied strain, respectively. The sensitivity (GF) and the working range are a pair of parameters that restrict each other. The strategy of increasing sensitivity often reduces the working range and vice versa.
More CNTs content means a higher tightness of the conductive film, so it is harder to break the conductive networks under large strains. Therefore, the working range of the sensor increased and GF decreased when the volume of the CNTs/ethanol dispersion changed from 0.3 mL to 0.5 mL. As for the sensors made of the 0.5–0.7 mL dispersion, the contents of the CNTs had reached the critical point and were almost unchanged, so the working range, as well as GF, did not change too much.

Figure 3d–f demonstrates that the strain sensors obtained by the different conductive films exhibit different electrical properties. The three kinds of sensors we fabricated are, respectively, named “1 layer-cured”, “1 layer-transferred”, and “2 layers-combined”, corresponding to the name of the conductive films. The “1 layer-transferred” sensor exhibits the highest sensitivity and the most limited working range due to its small content of CNTs and the penetration degree of the PDMS into the CNTs networks, which leads to resistance changes substantially with strain. Compared with the “1 layer-transferred” sensor, the “1 layer-cured” one has a wider working range and smaller sensitivity, which is attributed
to a higher penetration degree of the PDMS into the CNTs networks. Among the three sensors, the “2 layers-combined” sensor is the one with the best conductivity due to having the highest CNTs content, largest working range, and smallest GF. In consideration of the conductivity and working range, the “2 layers-combined” sensor is more suitable for practical application in detecting large strains.

The structure of the sensor has a certain effect on its performance, as shown in Figure 3g. We designed two kinds of sensors with different structures, named the PC (PDMS/CNTs) structure and PCP (PDMS/CNTs/PDMS) structure, respectively. The strain sensor without a package (PC structure) has a higher sensitivity and a wider working range than the packaged PCP sensor. For the PCP sensor, the post-cast PDMS increases the overall thickness of the sensor, which makes it more prone to break under large strains, resulting in a narrow working range. Additionally, due to the protection of the double-layer PDMS, the binding force between the CNTs and PDMS is strong, and the CNTs film is not prone to deformation, so the sensitivity of the PCP sensor is lower than that of the PC sensor. However, the CNTs films exposed to the environment are susceptible to wear and tear, which heavily impacts the conductivity and conductive stability of electronics. Therefore, the packaging with the PDMS is indispensable for sensors in reality.

The PCP strain sensor self-assembled from the 0.5 mL dispersion exhibits linear current-to-voltage characteristic, as shown in Figure 3h, indicating its perfect ohmic resistance behavior. In addition, the trend of current change with strain under the strain rate of 50 mm min⁻¹ is shown in Figure 3i. It is worth mentioning that subsequent tests are based on this kind of PCP sensor.

In Table 1, we list the main evaluation parameters of the flexible strain sensors with a sandwich-like structure (PCP structure), which are based on Marangoni-driven self-assembly and other methods. Compared with the sensors made of graphene, our sensor exhibits a wider working range and more excellent stability, thanks to the stretchability of the CNTs and our designed fabrication process. In addition, our low-cost sensor is still competitive in terms of raw material consumption and large-scale production compared with other sensors. Due to its comprehensive performance, our sensor is promising to apply in human motion detection.

As illustrated in Figure 4a, when the PCP strain sensor stretched under tensile rates of 50 mm min⁻¹, 100 mm min⁻¹, and 200 mm min⁻¹, the sensing performance in the 0%–30% strain range remains basically unchanged, suggesting the excellent elasticity and ultra-fast response rate of the sensor [46,47]. Figure 4b offers details of the performance of the sensor under different strains. When the PCP sensor was stretched by 5%, 10%, 20%, and 30% strain, the electrical signals showed an obvious difference, with ∆R/R₀ of 0.04, 0.12, 0.24, and 0.48, respectively. The ∆R/R₀ was relatively small under a 5% strain and sharply increased under a strain of 30%. When the sensor was stretched to the same strain for several times, the ∆R/R₀ kept consistent. As can be seen from Figure 4c, the PCP strain sensor shows superior durability performance and ∆R/R₀ remains stable after 8000 stretch-
ing/releasing cycles between 0% and 30% strain under the rate of 200 mm·min$^{-1}$. With the increase in cycle numbers, the $\Delta R/R_0$ changes of the sensor decreased from 0.41 to 0.31, and the $\Delta R/R_0$ curves showed a downward trend, which was mainly because of the fatigue of the substrates and the destruction and reconstruction of the CNTs network [13]. The cycle test proves that our high-stable PCP strain sensor can meet the requirements of electronic devices.

![Graph](image)

**Figure 4.** (a) Relative resistance changes of the PCP strain sensor under 30% tensile strain with different tensile rates. (b) Relative resistance changes of the PCP strain sensor under different tensile strains. (c) Stability test of the PCP strain sensor under the typical strain of 30%. Insets are enlarged data of different cycles.

### 3.3. Application of PCP Strain Sensors

The PCP strain sensors we designed can be used to detect various body motions based on these excellent performances. With the help of tapes, they can be adhered to various joints of the human body because of their soft and flexible characteristics.

As shown in Figure 5a, the sensor could detect the bending of the finger precisely. When the finger adjusted from 0° to 45°, $\Delta R/R_0$ increased from 0 to about 0.6, and then $\Delta R/R_0$ recovered to 0 as the finger joint returned to 0°. When the finger was bent to different degrees, the resistance changes were also different. After the sensor was bent and released several times, the sensing signal was still clear and stable. Additionally, we attached PCP strain sensors onto the tester’s wrist, elbow, and knee to monitor the motion of bending, shown in Figure 5b–d. The sensors responded differently in resistance change when the joints were bent to different degrees and the different joints also corresponded to different electrical responses.
In addition, pressing the sensor with fingers (Figure 5e) and twisting the sensor (Figure 5f) could also be detected in the resistance change, respectively. It is worth mentioning that subtle body motions, including frowning, blowing, and pulse beating, were also detected (Figure 5g–i).

The above experiments prove that the PCP strain sensor is promising to be applied to the detection of human motion signals.

4. Conclusions

In this paper, we designed a high-performance flexible strain sensor with a simple strategy. A single layer of CNTs film was self-assembled in a few seconds due to the Marangoni effect. The tightness and thickness of CNTs film are adjustable within the limits by controlling the injected volume of the CNTs/ethanol dispersion. The CNTs film obtained by the 0.5 mL 1 mg·mL$^{-1}$ CNTs/ethanol dispersion on 100 cm$^2$ water exhibits a thickness of 38 nm, a sheet resistance of 7.3 kΩ/□, and optical transmittance at 550 nm of 66.9%, respectively. After transferring the CNTs film to PDMS twice and packaging it with PDMS, we obtained the sandwich-like PCP strain sensors. The content of the CNTs (including the injected dispersion volume and the layer counts of CNTs film attached to PDMS) and the fabricating structure of sensors have an enormous influence on the sensing property. The typical PCP sensors show satisfactory sensitivity (GF = 3.4), a large working range (89%), and excellent cyclic stability (> 8000 cycles). In addition, they perform outstandingly in sensing tensioning, bending, pressing, and twisting. The experimental results indicate a
remarkable potential for the PCP strain sensors to apply in human motion detection and electronic skins.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/.../coatings13061026/s1, Movie S1: Process of Marangoni self-assembly and transfer.

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**References**


51. Liu, Q.; Chen, J.; Li, Y.; Shi, G. High-performance strain sensors with fish-scale-like graphene-sensing layers for full-range detection of human motions. ACS Nano 2016, 10, 7901–7906. [CrossRef]

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