TRIBOELECTRIFICATION BASED ACTIVE SENSOR FOR LIQUID FLOW AND BUBBLE DETETECTING

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ABSTRACT

This work presents a self-powered liquid flow and bubble detection sensor based on the effect of contact-electrification between liquid and solid interface. Charge is driven by the electrostatic induction to flow across outer load without power supply. Single-step fluorocarbon plasma treated PDMS with wrinkle pattern is employed to contact with liquid, which could enhance the electric performance and protect electrode. Interdigital electrode is utilized to detect the liquid flow direction and velocity, while the grounded branch makes it capable to detect bubble. This new-designed active sensor with the advantages of simple structure, stability, multifunction and scalability has a promising application in microfluidic sensor system.

INTRODUCTION

Micro total analysis system (μTAS) or lab on a chip has become a well-known and powerful analysis platform for biological, chemical analyses [1]. As one type of microfluidic device, the droplet based microfluidic devices have been given significant attention due to their advantages in high throughput applications [2]. Typically, large scale channel networks are involved in a droplet microfluidic device, leading to a fundamental challenge in managing droplet traffic [3]. To control the droplet traffic in a complex system, real-time detection of liquid flow direction, flow velocity and bubble is required. To date, two most common methods of liquid flow detection are optical and electrical sensing. These methods usually involve bulky components that include microscope, CCD camera, circulating system with high energy consumption, which limit the use for complicated devices [4]. Although new mechanisms based on capacitive and resistive changes have been proposed and demonstrated for miniaturization and different applications, the need of outer power source and complex readout circuits restrict their use for some practical situations [5].

Recently, many kinds of triboelectric nanogenerators (TENG) based on the coupling effect of contact-electrification and electrostatic induction have been proposed and developed for harvesting various kinds of energy [6,7]. Benefited by its advantage of simple structure, sensitive to environmental variation, and self-power generation, TENG can be easily employed to act as a mechanical sensor from various mechanical sources [8,9]. As one kind of contact pair of TENG, the contact-electrification between water and solid surface has been developed to harvest water wave and droplet energy from environment [10]. Meanwhile, some self-powered sensors in microfluidics have been reported for detecting the liquid flow rate and ion concentration [11,12]. However, due to the lack of electrode pattern design, the existing devices aren't capable to detect the liquid and bubble flow in microfluidics at the same time.

Herein, we propose a self-powered liquid flow and bubble detecting sensor embedded in a microfluidic system. The effect of contact-electrification between water and solid interface is employed to generate electricity in outer circuit, resulting in the purpose of active detecting. Single-step fluorocarbon plasma treated PDMS with wrinkle pattern is used to increase the electric performance. To distinguish different signal produced by water moving in the microfluidics, an interdigital-shaped electrode is introduced, which enable us to detect the liquid flow direction, and velocity. By connecting one branch of the electrode with ground, we successfully detect the existence of bubbles.

STRUCTURAL DESIGN

The schematic diagrams of the device are shown in Figure 1. Glass is chosen as the substrate to support the whole device. Interdigital ITO electrode is fabricated on the substrate, which is a core component for our device. Wrinkle patterned PDMS by fluorocarbon plasma is fabricated on the ITO electrode, which has a same size with the PDMS micro channel. To demonstrate the function of this device, two reservoirs are added in this work.

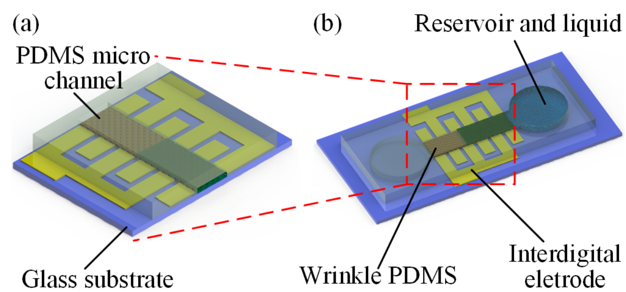

Figure 1: Structural diagrams of the active sensor and its demonstration in a microfluidic device with two reservoirs.

FABRICATION PROCESS

The fabrication process is illustrated in Figure 2. Firstly, the master mold with the microfluidic channel pattern is fabricated by laser cutting a PMMA plate (Figure 2a). Then the structure on master mold is transferred to PDMS by soft lithography, and the transferred PDMS channel serves as the top part afterwards. The bottom part started with a laser pattered interdigital ITO electrode on glass substrate (Figure 2d). Liquid PDMS is afterwards spin-coated on the electrode and patterned to have a same size with the channel of top part. After 1 min curing, a fluorocarbon plasma treatment is carried out in an inductively coupled plasma etching (ICP) machine to fabricate wrinkle structure [13,14]. Then the plasma treated sample is cured at 90℃ for 30 minutes. Finally, the processed top part and bottom part are bonded together.

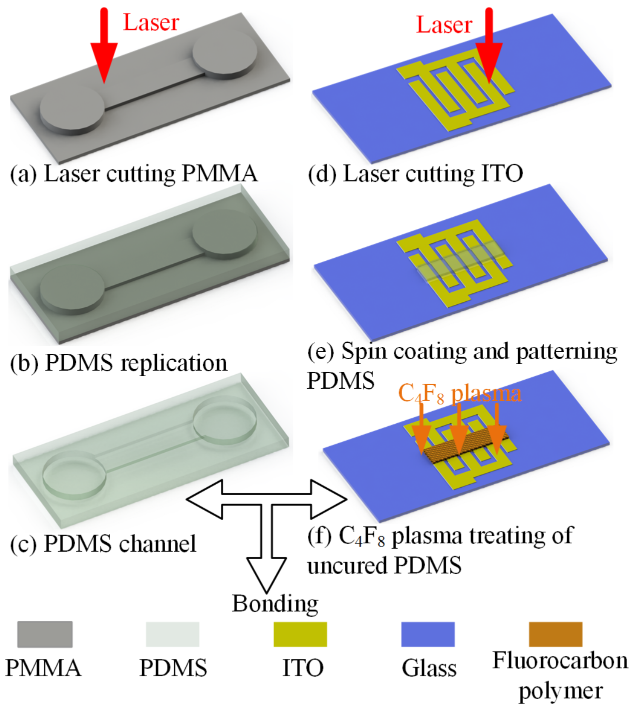

Figure 2: Fabrication process for the active sensor with two reservoirs.

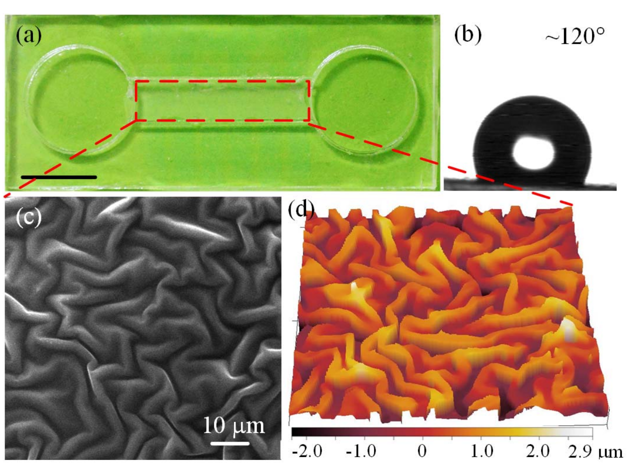

Figure 3: (a) Photographs of the device. (Scale bar 1 cm) (b) The contact angle of 3 μL water on the wrinkle PDMS. (c-d) SEM image and corresponding 3D view of the wrinkle structure.

Figure 3a shows the fabricated device, with the channel size of 24 mm×6 mm×1 mm. The channel in the bottom part is covered by wrinkle patterned PDMS, whose contact angle is about 120° (Figure 3b). This hydrophobic layer would greatly enhance the electric performance of the device [12]. The SEM image and corresponding 3D view of the wrinkle structure are shown in Figure 3b-d, respectively. The wavelength of this wrinkle structure are about several micro meters (Figure 3c-d).

WORKING PRINCIPLE

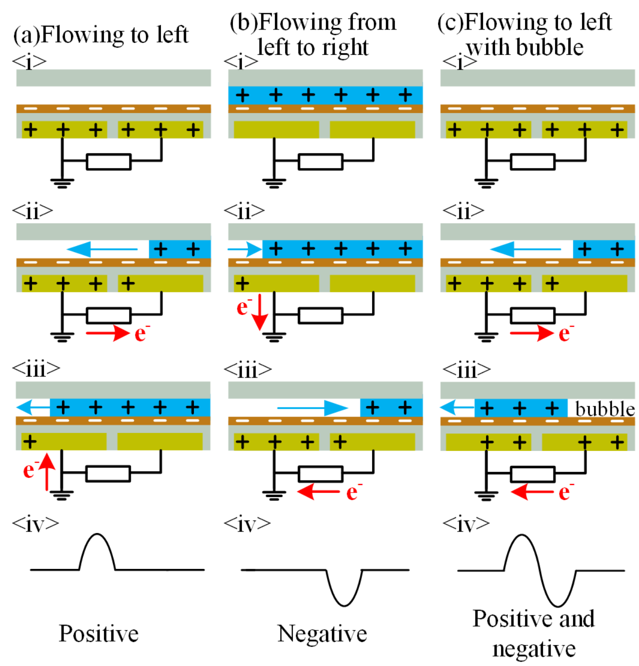

Figure 4: Working principle for the active sensor to detecting and distinguish liquid flow direction and bubble.

The working principle of the proposed device is diagramed in Figure 4. When a finger is pressed on the right reservoir, water flow will move from right to left. After several cycles of water flowing back and forth in the channel, negative charge would accumulate on the surface of wrinkle PDMS due to the contact electrification between water and wrinkle PDMS. Meanwhile, positive charge would be inducted on the interdigital electrode to reach the state of electrostatic equilibrium. Afterwards, during water flowing to left as shown in Figure 4a, electron would transfer from ground across outer load to the right electrode only when water flow across the right electrode. This would lead to a current flowing from the right electrode to the ground, producing a positive current. Similarly, during the process of water flowing from left to right as shown in Figure 4b, electron would transfer across the load to the ground only when the water flows back across the right electrode. Consequently, a negative current would be observed. Additionally, if bubble existed in the liquid flowing process as diagramed in Figure 4c, a positive current would also be observed when water flow across the right electrode, which keeps the same with the case in Figure 4a. But when water liquid continue flow on the left electrode and bubble on the right electrode, there would no charge in the channel to balance the negative charge on the wrinkle PDMS. Thereby, electron would flow from the right electrode to the left electrode to reach the electrostatic equilibrium state, resulting in a negative current signal. During the whole flowing process in Figure 4c, a consecutive positive and negative current signal would be observed. As a result, we can easily distinguish water flow direction and the existence of bubble by simply observing the current signal of outer circuits produced by water flowing in the microfluidics channel.

ELECTARICAL MEASUREMENT

The output voltage was measured using a digital oscilloscope (Agilent DSO-X 2014A) via a 100 MΩ probe (HP9258), and the current was amplified through a SR570 low noise current amplifier from Stanford Research systems. The water movement in the microfluidic channel is driven by finger periodically pressing on the right reservoir.

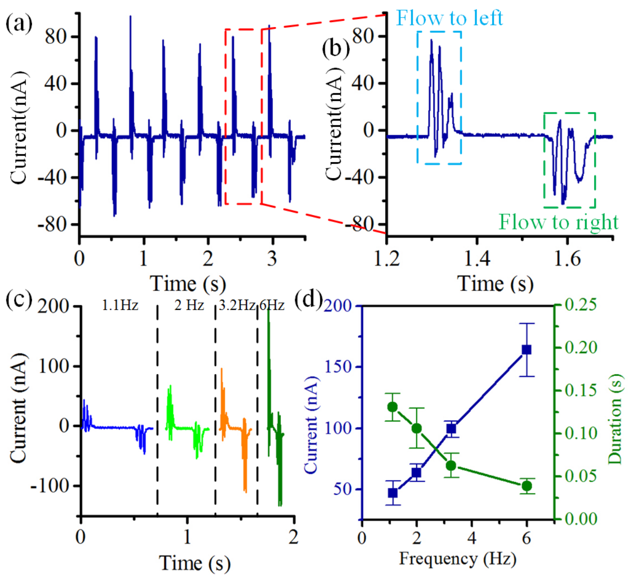

Figure 5: (a-b) Output current signal and enlarged waveform in single cycle when liquid flow to left and right. (c-d) Output current signals, values and corresponding duration time under different flow frequencies.

The output current is plotted in Figure 5a, alternate current with a peak value of 80 nA is observed when liquid flowing periodically. During a flowing cycle, three continuous positive signals appeared corresponding to the liquid flowing to the left over the ungrounded branch, while three negative signals are observed when water flowing back (Figure 5b), which is consistent with our description in working principle. So the flow direction of liquid in the microfluidic channel could be easily obtained by observing the current waveform. Additionally, the velocity of flowing liquid was related to the peak value and duration time (i.e. the time liquid flow from one side to the other) of the electric signal (Figure 5c). When the frequency of press was slow (i.e. 1.1 Hz), the peak value was smaller and the duration time was longer. But when the frequency of press was fast (i.e. 6 Hz), the peak value and the duration time became larger and shorter, respectively. This conclusion can be further verified by the statistic results plotted in Figure 5d. The peak value increased with the press frequency while the duration time decreased with it, both of which shown good linearity.

Figure 6 shows three examples of electric signals for bubble detecting. Generally, a reversed signal would be measured once a bubble existed in flowing liquid in the same flowing direction. In Figure 6a, a negative consecutive current signal is observed, so the water in the channel flowed back from left to the right. A positive signal appeared in the second peak, thus the bubble existed in the liquid. Similar results when bubble in different position and water flowing to different direction shown in Figure 6b-c.

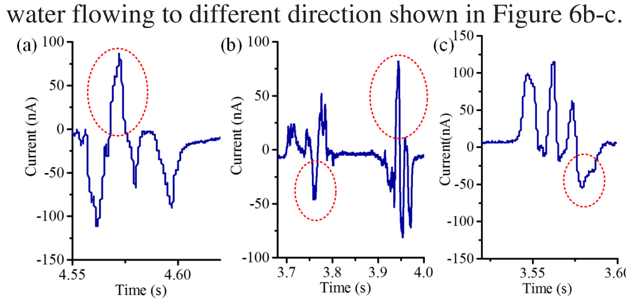

Figure 6: Waveforms of the active sensor detecting the existing of bubbles (i.e. marked with red cycle).

CONCLUSIONS

In summary, a novel contact-electrification based self-powered liquid flow and bubble detection sensor embedded in a microfluidic system is proposed, fabricated, analyzed, and characterized. Using the effect of contact-electrification between water and solid to generate electricity in outer circuit, this sensor could produce electric signal without outer power supply. Employing the single-step fluorocarbon plasma to treat PDMS with wrinkle pattern, we successfully obtained a hydrophobic surface and enhanced electric performance of the device. The one branch grounded interdigital electrode enable us to monitor the liquid flow in real-time, including flow direction, velocity and the existence of bubble. By electric characterization, we can successfully distinguish the flow direction from the polarity of electric signal. The velocity can be observed and further calculated by the peak value and duration time of electric signal. The existence of bubble can be detected by the reversed signal in a consecutive waveform. Our work successfully and systematically demonstrates the possibility of using the effect of contact electrification to monitor the liquid flow in microfluidics in real time. This undoubtedly provides a powerful and simple alternative tool in the microfluidic sensor system.

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