A LOW-COST FLEXIBLE ELECTROCHEMICAL ACCELEROMETER USING GRAPHENE-INTEGRATED MICROCHANNEL

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ABSTRACT

This paper reports a novel electrochemical accelerometer for applications of wearable systems and smart skins. An original flexible accelerometer based on graphene electrodes and a PDMS microchannel on polyimide flexible print circuit (FPC) has been achieved by low-cost fabrication process. Instead of expensive platinum electrodes, a graphene layer was transferred to FPC to function as chemical inertness sensitive electrodes. To simplify process steps and reduce fabrication cost, the microchannel on FPC was obtained without lithography process by using screen printing PDMS lines. In shock exciter experiment, the accelerometer was tested under 20g shock acceleration, providing 39.5mv/g (0.40μA/g) sensitivity. This microchannel electrochemical device can not only be used for acceleration sensing, but also provide more possibilities in flexible multi-sensor system, for example pressure, temperature and tactile sensing applications.

INTRODUCTION

With the fast development of wearable devices and smart skins, the demand for sensors compatible to flexible electronics is significantly increasing, and flexible MEMS sensors tend to be comprehensive and integrating of multi-physical sensors. As accelerometers play important role in medical monitoring and motion-sensing, flexible accelerometers have huge potential in those wearable systems [1].

Compared with silicon MEMS accelerometers, fluidic electrochemical accelerometers, or accelerometer based on molecular electronic transducer, have simpler structure and higher impact resistance, especially without tiny size movable inertial proof mass and cantilever which need precision lithography processing. They also show more compatibility to simplify fabrication process with flexible material and provide high performance and sensitivity in low-frequency range [2, 3]. With the development of MEMS technology, electrochemical accelerometers evolve from macro-size design to micro accelerometer which is using a droplet in a microchannel and MEMS electrode with a micro-pitch for acceleration sensing [4]. It has entered the size range which allows highly integrated applications on flexible substrate.

Graphene, with high conductivity, excellent chemical inertness and mechanical strength, has been used as an excellent catalytic electrode material in dye-sensitized solar cells and super capacitors [5, 6]. Based on those properties, graphene is also a competent alternative of expensive platinum to fabricate chemical inertness electrode in flexible electrochemical accelerometers. As the advantages of graphene material and electrochemical accelerometer which are mentioned above, a MEMS accelerometer based on graphene electrodes and electrolytic droplet in a microchannel is developed in this paper. At the same time, it is also desirable to combine the fabrication of electrochemical accelerometers with flexible materials and processes to develop flexible accelerometers for wearable sensor applications, and provide a low cost solution based on flexible printed circuit processing.

PRINCIPLE

The basic principle of this accelerometer combines the mechanical and electrochemical parts in signal processing. From a mechanical point of view, the sensor is similar to conventional acceleration with masses and springs. The iodide electrolytic droplet in PDMS channel acts as mass block which is sensitive to acceleration, while the air column between iodide electrolytic drop and seal cap acts as gas spring to push electrolytic drop back to original position after shock (Fig. 1).

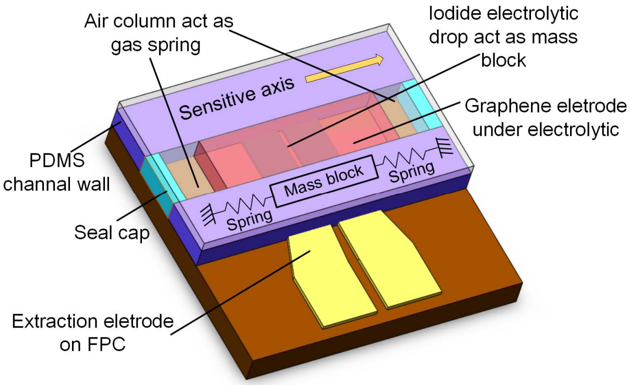

Figure.1 The structure of electrochemical accelerometer on flexible print circuit with graphene electrode and printed PDMS microchannel.

In the case of external acceleration, the droplet mass block is driven by inertial force and displaced in microchannel. Since the graphene electrode is fixed on the channel wall, the droplet and the ions in it can move relatively to the graphene electrode. This relative movement can be detected by the electrochemical method. The main factor that limits the sensitivity of the device is the size of the droplet, which means the mass of the proof mass, and directly impacts the inertia force. The length and thickness of the air column also affect the stiffness of the air spring and the displacement of the droplet. In actual devices, the viscous force of the channel wall and the surface tension of the liquid droplet will also affect the response to external acceleration. Strong surface tension and a small contact angle with the channel wall help to keep the shape of the droplet in the channel, and avoid changes in device performance.

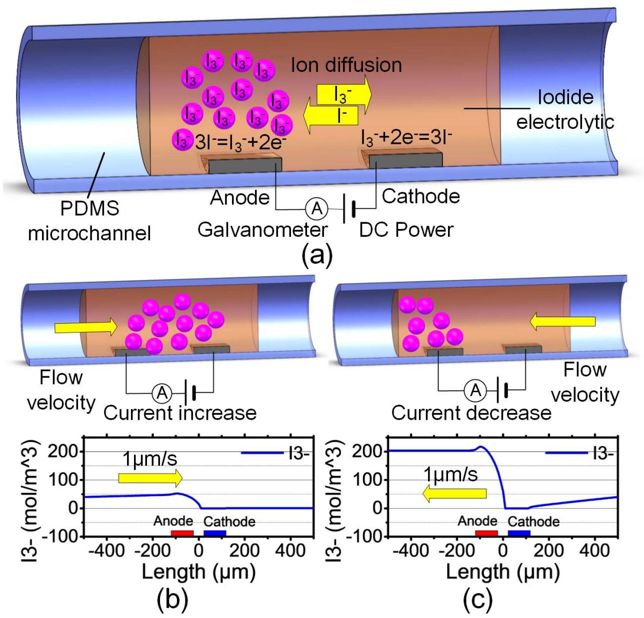

Figure.2 The principle of microchannel electrochemical accelerometer (a). The simulation result of ion gradient in forward flow(b) and reverse flow(c).

From the electrochemical point of view, the simplest accelerometer can be simplified into two electrodes immersed in iodine electrolyte. When voltage is applied on the two graphene electrodes with a small interval gap, the I_3^- ion is generated on anode and consumed on cathode, which forms an ion gradient in iodide electrolytic [7]:

reduction of triiodide on the cathode:

$$3I^- = I_3^- + 2e^-;$$

oxidation of iodide on the anode:

$$I_3^- + 2e^- = 3I^-.$$

The current between two electrodes depends on the diffusion rate of I_3^- (From the anode to the cathode). In the case of external acceleration, the acceleration gives rise to the movement of the electrolytic droplet in microchannel, leading to the transferring of I_3^- ion, (Fig. 2). As a result, the current between two electrodes changes with the variation of ion gradient. The changes of current signal can be detected by a current amplifier to measure the external shock acceleration. When the droplet moves from the anode toward the cathode, the measured current increases, and the measured current decreases as the droplet moves backwards. Due to this sensing principle, the sensor is able to respond to very low frequency acceleration variations. However, it cannot detect static acceleration. On the basis of the two electrodes design, more complex electrochemical accelerometer structure can be developed to enhance the ability of the accelerometer.

EXPERIMENTAL METHODS

Fig. 3 illustrates the fabrication process of FPC based graphene electrochemical accelerometer. To start with, the copper electrode pattern is prepared on the FPC circuit board by the photosensitive ink and the ferric chloride etching solution in PCB process, and used as an extraction electrode. In the common FPC process, the copper electrodes spacing can be as small as 0.3mm. In the next step, graphene layer is transferred to the flexible print circuit by water transfer printing [8]. Graphene can cover the step in the edge of corrosion copper foil (20 ~ 30um), and form ohmic contact with copper foil. Although other transfer methods which are compatible with the flexible circuit board materials can also be used, the advantages of using water transfer method is a simple operation with only one-step transfer process, and easy to locate graphene on the copper foil electrode. After transferring, graphene is etched to form micro-pitch between the electrodes.

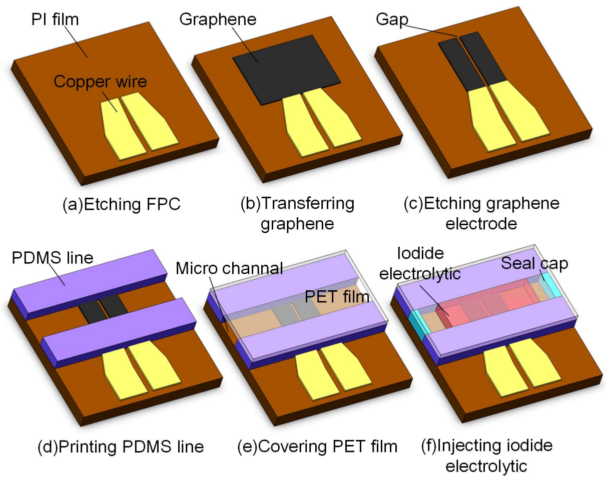

Figure.3 The process of FPC based graphene electrochemical accelerometer. Screen printed PDMS lines and bonded PET film are used in microchannel fabrication.

Later a PDMS micro channel is made on FPC by screen printed PDMS lines and bonded PET film. At First, The PDMS is blended, half cured to a suitable viscosity and screen printed onto the FPC to form millimeter level PDMS lines, followed by bonding with the oxygen plasma activated PET film and final curing. The cured PDMS line forms the channel wall, and the line spacing forms the flow path. After bonding an 150μm high, 5mm wide, and several centimeters long micro-channel can be prepared to contain the electrolyte. In this process PDMS covers the contact area of graphene and copper foil, on the one hand to protect the contacts and avoid the breakage of graphene; on the other hand, to avoid the electrolyte reaction occurs in the galvanic cell of copper foil and graphene, which causes copper foil to corrosion. After channel fabrication, air and liquid iodide electrolytic are injected into channel by a micro injector. Finally, the opening channel is sealed by UV-curing soft resin cap.

RESULTS AND DISCUSSION

The fabricated graphene electrochemical acceleration sensor is shown in Fig. 4. The sensor design is based on graphene intergraded PDMS channel fabricated on a commercial flexible print circuit (FPC), which was made by PI subtract and copper conductive layer, as presented in Fig. 3. The three-layer structure with microchannal can be observed clearly under the microscope. As a result of semi-fluid state PDMS, the channel walls automatically smoothed after screen printing. A photograph under microscope shows the 20μm micro-pitch which was etched on the graphene electrode, and part of the PI substrate was also etched to form a dark trace.

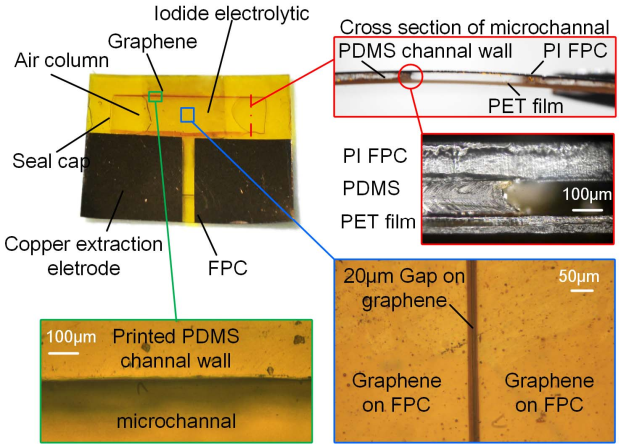

Figure.4 The photographs of fabricated FPC based graphene electrochemical accelerometer, which show channal wall and micro-pitch on graphene electrode.

As shown in Fig. 5, the accelerometer was tested using a signal amplifier circuit and a pneumatic shock exciter test rig, with a reference accelerometer for the measurement of applied acceleration. The test circuit applied a constant voltage between the electrodes and converts the current flowing through the cathode electrode into a voltage output by a two stage amplifier. The accelerometer is fixed on the shaker with a single axis silicon standard accelerometer as reference.

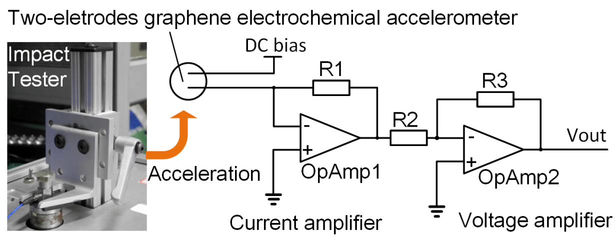

Figure.5 The accelerometer is tested with pneumatic shock exciter test rig (left) and signal amplifier circuit(right) in experiment.

The response waveform of graphene electrochemical accelerometer was compared with reference accelerometer in Fig. 6. The graphene electrochemical accelerometer provides 39.5mv/g (0.40μA/g) sensitivity in 20g shock testing. The result also indicates 60ms response time and second level recovery time after impact, which is caused by the long rebuilding process of ion gradient in this two electrodes structure, and the relative large electrode area. With the application of symmetrical four-electrode structure and more sophisticated electrode processing, the performance of frequency response can be improved in future.

Since this sensing principle is based on the relative motion of the droplet and channel walls, this device also has potential in sensing other physical quantities. For example, the deformation of a pipe under pressure, and the movement of liquid due to volume expansion under a temperature change, can also be sensed by the similar structure, and can be integrated in the same FPC board by the same process. These possibilities show potential for flexible multi-sensor integration systems development.

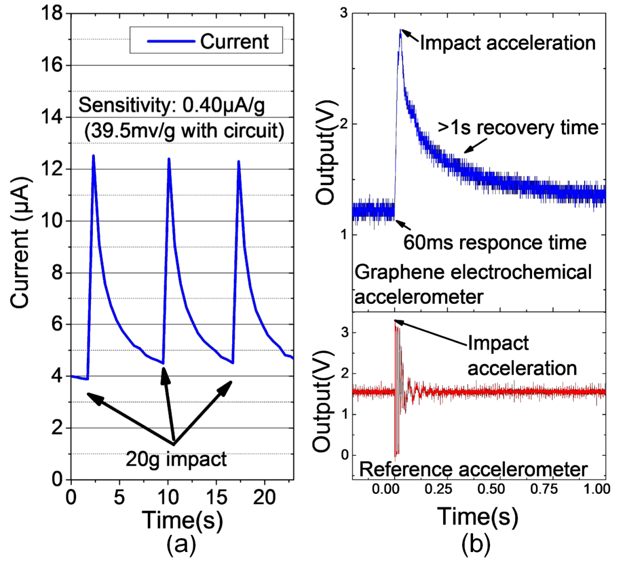

Figure.6 The two-electrodes graphene electrochemical accelerometer shows 0.40μA/g (39.5mV/g with circuit) sensitivity to 20g shock acceleration(a), the output waveform is compared with a reference accelerometer(b).

CONCLUSION

In this paper, we report a flexible electrochemical accelerometer with graphene integrated microchannel. The accelerometer is fabricated on a flexible PCB by screen printing PDMS lines, and graphene is used as an inertness electrode instead of common platinum electrode in former electrochemical accelerometer to reduce fabrication cost. This structure is sensitive to external acceleration variation, provides 39.5mv/g (0.40μA/g) sensitivity in 20g shock acceleration.

This accelerometer on flexible PCB is able to be integrated into a flexible sensor system with great potential in the further development of wearable systems and smart skins. Besides acceleration sensing, the architectures of this device can also provide possibilities for other physical quantities sensor in flexible multi-sensor integration systems, with functions of pressure, temperature and tactile sensing.

ACKNOWLEDGEMENTS

The authors wish to thank Dr.Tingting Yang and Prof.Hongwei Zhu from School of Materials Science & Engineering, Tsinghua University, and Dr.Bing Deng and Prof.Hailin Peng from College of Chemistry and Molecular Engineering, Peking University, for their assistance in providing high quality CVD graphene materials.

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