ENVIRONMENT-FRIENDLY WEARABLE THERMAL FLOW SENSORS FOR NONINVASIVE RESPIRATORY MONITORING

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ABSTRACT

We report on a low-cost, environmentally friendly and wearable thermal flow sensor for non-invasive monitoring of human respiration. The sensor can be manufactured in-house using pencil graphite as a sensing hot film and biodegradable printing paper as a substrate, without using any toxic solvents or cleanroom facilities. The hot film flow sensor offers excellent characteristics such as high sensitivity, high signal-to-noise response to airflow and outstanding long-term stability. We further demonstrate a patch-type wearable sensor for monitoring human respiration. The results indicate that the sensor may be utilized to medically monitor sleep quality and other personal health concerns.

INTRODUCTION

Conventional MEMS (Micro-Electro-Mechanical Systems) sensors have been aimed at high sensitivity, fast response, miniaturization ability, mass production and low cost [1]. As such, silicon and silicon carbide materials have been employed to fabricate various highly sensitive sensors, including temperature sensors [2-4] and strain sensors [5,6], and thermoelectric devices [7].

Alternatively, the research community has paid much attention to future MEMS sensors which demonstrate flexibility/stretchability for wearable applications such as monitoring human motion, sleep patterns and other healthcare applications [8-10]. For example, measuring respiration is an effective method which has been employed to support the therapy for respiratory diseases. However, existing systems have normally exploited nasal cannulas, which include two small pipes to be invasively inserted into the nostrils, resulting in breathing discomfort for patients. Therefore, there is a great demand for the development of wearable flow sensors for noninvasive respiratory monitoring [11-13].

Recently, proof of concept of various flexible and wearable electronic devices has been successfully demonstrated using pencil drawn shading on paper (GOP) [14,15]. Moreover, this graphite shading on paper is a simple but effective approach to fabricating low-cost flexible sensors for healthcare, owing to the porosity and flexibility of sheets of papers. Previous work [16] has shown that pencil-drawn graphite on paper could be utilized for developing thermoresistive sensors, owing to the high temperature coefficient of resistance of pencil graphite materials.

In this study, we report a cleanroom-free fabrication of a flexible sensor. The sensor was fabricated in-house using a simple pencil-drawn-on-paper technique, followed by a laser cutting approach. Excellent performance characteristics of the sensor were observed, exhibiting high sensitivity, a high signal-to-noise ratio and good long-term stability. We also successfully demonstrated the non-invasive monitoring capability of the sensor, which could monitor human respiration in real-time with high sensitivity.

FABRICATION OF THE SENSOR

Structure of the sensor and working principle

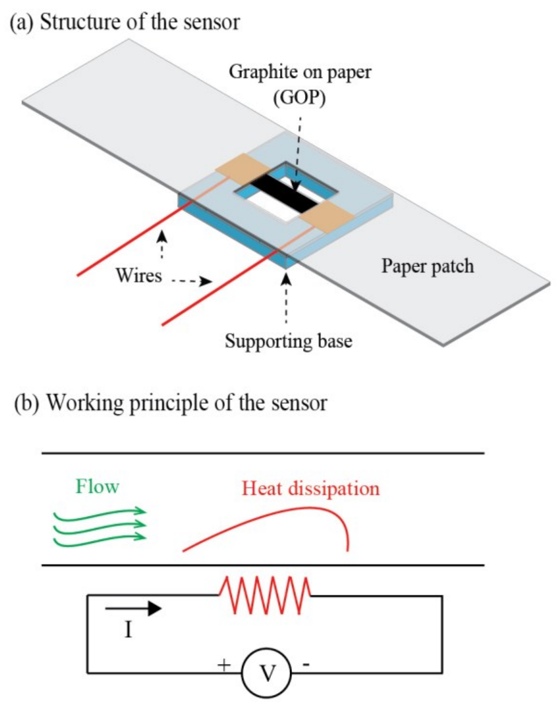

Figure 1: Schematic sketch of (a) structure and (b) principle of the flexible thermal flow sensor

Figure 1a shows the structure of the sensor, which consists of a graphite shading drawn on a paper (GOP) sensing layer, a supporting base and a paper patch. The design utilizing the supporting base for the sensor helps avoid resistance changes due to the piezoresistive effect of graphite under bending [10,15]. Moreover, the paper patch is used for wearing purposes, owing to the flexibility of the printing paper. The graphite sensing layer, deposited to the paper substrate, works as a thermoresistive sensing element.

Figure 1b shows the working principle of the sensor, which is based on the convective heat transfer between the graphite trace and the surrounding environment [16-18]. When a large current is applied, the temperature rises in the sensor and reaches a steady state. As an air flow passes around the sensor, the temperature decreases and

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the resistance of the sensor increases due to the negative temperature coefficient of resistance of the graphite drawn on paper [16]. By detecting the change in the electrical resistance of the sensor, the air flow velocity can be measured.

Fabrication process

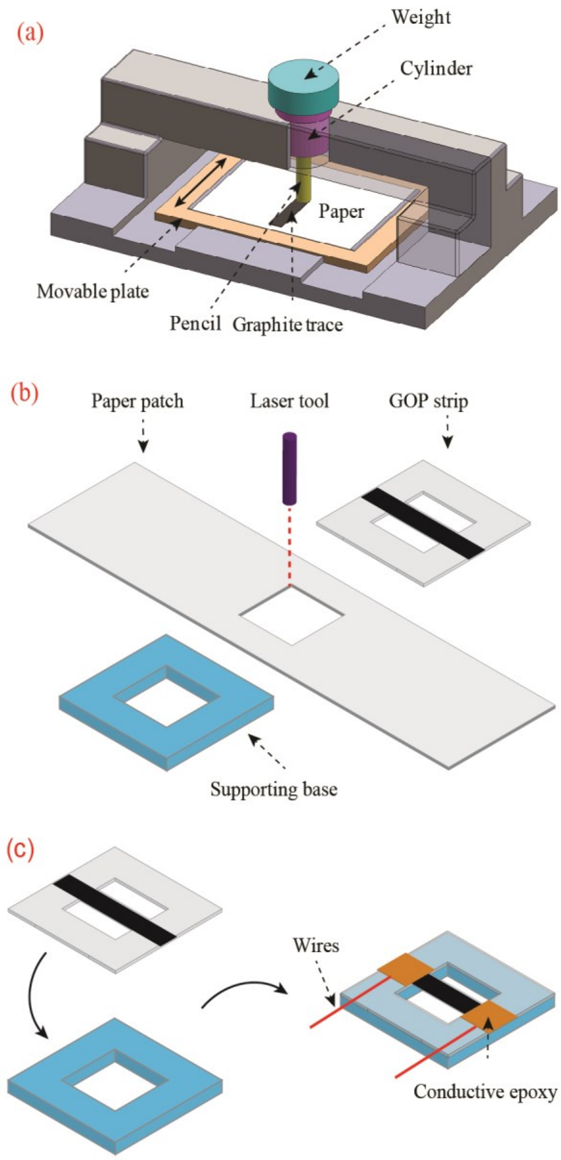

Figure 2: Fabrication process of the flexible flow sensors using a pencil drawing technique and a laser cutting method. (a) Drawing pencil trace on paper (b) Cutting strips, patches and supporting parts. (c) Assembly of GOP on supporting base and making interconnections.

Figure 2 shows the fabrication process of the flexible thermal flow sensor. First, a pencil trace was drawn on a printing paper using a mechanism as depicted in Fig. 2a. The pressure at the pencil tip was controlled using a constant weight and the movement of the printing paper created the pencil trace. The drawing process was repeated sufficient times to achieve good electrical conductivity of the pencil trace. In the next step, we utilized a laser cutter to make a GOP strip, a paper patch and a supporting base (Fig. 2b). The sensor was then assembled using double-sided tape (Fig. 2c).

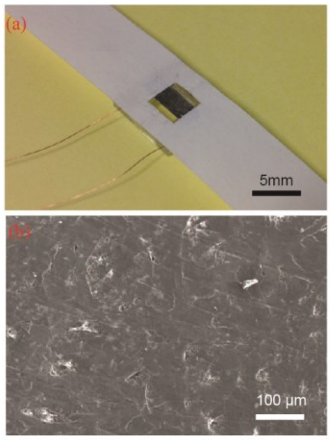

Figure 3: (a) Photograph of as-fabricated patch-type sensor. (b) Scanning Electron Microscope (SEM) image of graphite drawn on paper (GOP).

Figure 3a shows the photograph of the as-fabricated patch-type sensor, which is flexible; hence wearable due to the flexibility of the paper-based patch. Figure 3b shows the scanning electron microscopy (SEM) image of the pencil trace drawn on paper.

SENSOR CHARACTERISTICS

Performance of the sensor

Figure 4a shows the four-point measurement method which was used to measure the change in the electrical resistance of the sensor under airflow conditions. A constant current was applied and an output voltage was measured when airflow conditions changed. This measurement method has been commonly used for various thermal flow sensors reported in literature [17,18]. Figure 4b shows the real-time response of the sensor to the change of air flow rate, which indicates an increase in the differential output voltage with increasing airflow rate. As a constant current mode is employed, the increase in the output voltage indicates an increase in the electrical resistance of the sensor. As such, the resistance of the sensor increased with increasing air velocities and returned to the initial resistance when the air velocity equaled zero. This indicates good reversibility of the sensor signal. It is worth noting that a larger applied constant current offers a higher response signal. For example, at airflow velocity of 1 m/s, an applied current of 8 mA can generate a differential output voltage of approximately twice larger than that generated by an applied current of 6 mA.

Table 1: Sensitivity and power consumption of the sensor

Current (mA)	Sensitivity $(mV/(m/s)^{0.8})$	Power (mW)	Reference
6	33.8	45.3	This work
8	53.7	78.4	This work
9	12.9	18.3	[17]
10	100	120	This work

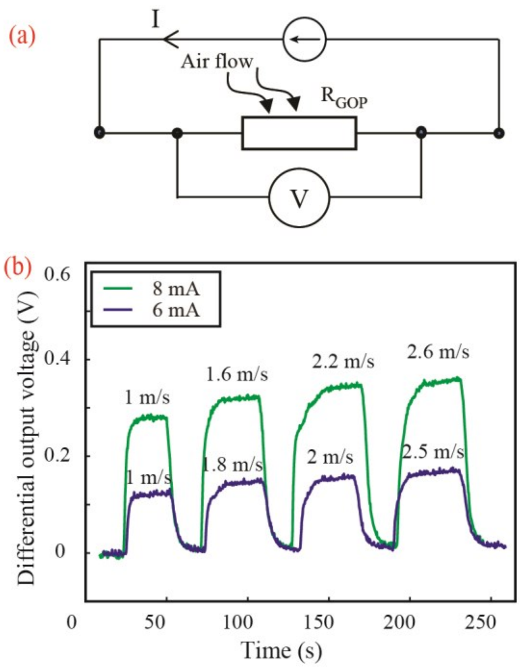

Figure 4: (a) Four-point measurement method. (b) Response of the sensor to different air velocities and constant currents.

The sensitivity and power consumption of the sensor is summarized in Table 1. The data shows that the GOP sensor has a high sensitivity and a relatively low power consumption, which is comparable to that reported in literature [17-22].

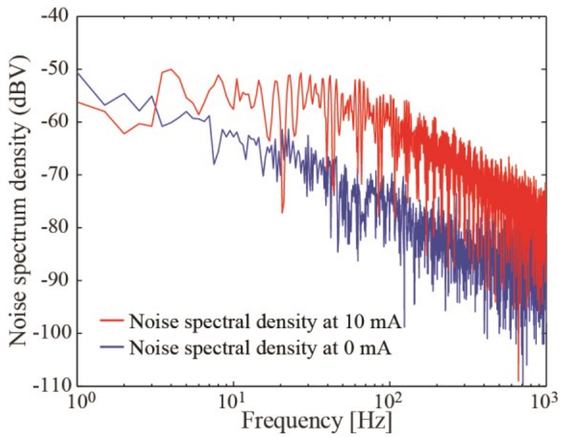

Figure 5: Noise spectrum of the sensor

Figure 5 shows noise spectrum density of the sensor, which was measured with an applied constant current of 10 mA and absence of current. It is evident that the noise level of the sensor at the large applied current is higher than that at zero current, which indicates a higher uncertainty for the sensor at high applied power.

To evaluate the stability of the sensor, we measured the response of the sensor over a period of six minutes at a constant air flow velocity of 1 m/s. The measurement was then repeated the following day. Figure 6 shows the measurement result for the sensor, which indicates a good repeatability and long-term stability of the sensor.

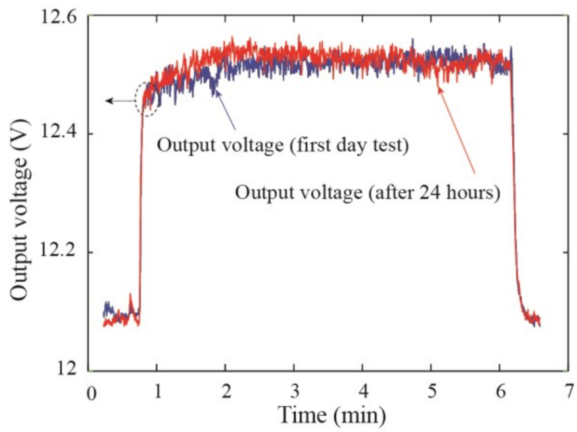

Figure 6: Long-term stability of the sensor.

Measurement of human respiration

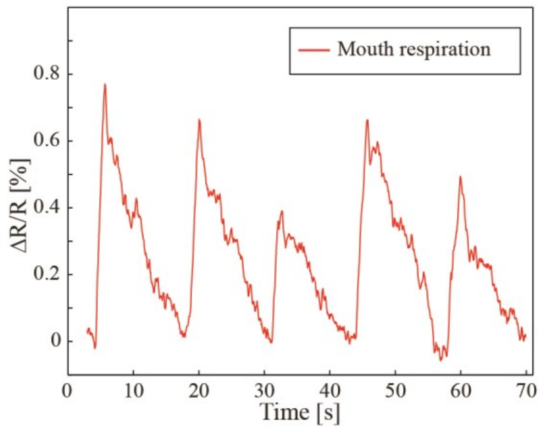

Figure 7: Response of the sensor to human respiration.

To demonstrate the feasibility of using the as-fabricated sensor for human respiration, we fixed the sensor on a desk to avoid the effects of agitation. When the flexible flow sensor was exposed to blowing by mouth, the high signal-to-noise ratios were measured as shown in Fig. 7. Five multiple tests using the mouth respiration was also conducted, which shows that the signal-to-noise ratios can be controlled by the speed of the mouth respiration. This result indicates that the as-fabricated flow sensor has a potential application for monitoring human respiration and sleep quality.

CONCLUSION

We successfully demonstrated the solvent-free fabrication of a flexible thermal flow sensor which can be fabricated in-house using a simple pencil drawing technique and a laser cutting approach. The sensor was characterized, exhibiting a high sensitivity, relatively low noise level and good long-term stability. The sensor was also proven to show the effective capability of monitoring human respiration in real-time. The results indicate the feasibility of this simple but effective method for fabricating flexible electronic devices for non-invasive monitoring applications such as measurements of human respiration, sleep patterns and other healthcare concerns.

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