PAPER-BASED PIEZORESISTIVE MEMS FORCE SENSORS

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ABSTRACT

This paper describes the development of piezoresistive MEMS force sensors constructed using paper as the structural material. The sensing principle of the paper-based sensor is based on the piezoresistive effect of conductive materials patterned on a paper substrate. The device is inexpensive (~$0.04/device for materials), simple to fabricate, lightweight, and disposable. The entire fabrication process can be completed within one hour in common laboratories with simple tools (e.g., a paper cutter and a painting knife), without requiring cleanroom facilities. The paper substrate allows easy integration of electrical signal processing circuits onto the paper-based MEMS devices. We demonstrated that the paper-based sensor can measure forces with moderate performance (i.e., detection limit: 120 μN, measurement range: ±16 mN, and sensitivity: 0.84 mV/mN), and applied the sensor to characterizing mechanical properties of soft materials. We also developed a paper-based weighting balance with a measurement range of 15 g and a resolution of 25 mg.

INTRODUCTION

The past three decades have witnessed the extensive development of MEMS devices and systems, which have found important applications in industrial and medical fields [1]. Silicon-based materials (e.g., single crystal silicon, polycrystalline silicon, silicon dioxide, and silicon nitride) are used as the primary materials for constructing MEMS devices. Despite recent efforts on utilizing other materials (e.g., polymer [2], diamond [3], and ceramics [4]) for MEMS construction, the material cost is still relatively high. In addition, the microfabrication process used for MEMS (especially for prototyping) is time-consuming (days for a single batch) and requires cleanroom equipments. Both materials and the use of cleanroom are expensive; and although the performance of silicon-based MEMS can be excellent, their relatively high cost has limited the applications and markets they can address.

We are interested in the development of new MEMS technologies, where the emphasis is on minimizing cost, and the ratio of performance to cost is maximized by minimizing cost rather than maximizing performance. As the materials serve as the basis for this exploratory progress, we have chosen paper. A conceptually selected effort to reduce the cost of diagnostic systems by developing paper-based diagnostic systems has opened a new venue of technologies [5-7]. Paper is readily available, lightweight, and easy-to-manufacture; it can be safely disposed of by incineration. As our first investigation of using paper for MEMS construction, we developed a paper-based pizoresistive force sensor and applied it to mechanical characterization of soft materials. Leveraging the same concept, we also demonstrated a paper-based weighting balance.

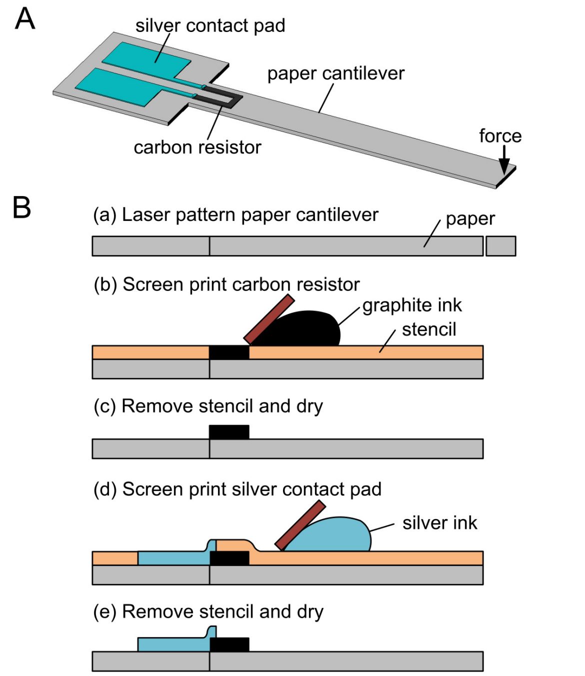

Figure 1: Paper-based piezoresistive force sensor. (A) Schematic view of a paper-based force sensor using a carbon resistor as the sensing component. (B) Fabrication process of the paper-based sensor.

EXPERIMENTAL DESIGN

Working Principle of the Paper-Based Force Sensor

The sensing principle of the paper-based force sensor is based on the piezoresistive effect of conductive materials patterned on a paper structure (a cantilever beam in this work). Many MEMS sensors (including commercial devices) also take advantage of the piezoresistive effect [8], but they are typically constructed from silicon-based semiconductor materials. Instead, we used paper as the structural material for construction of the devices.

Figure 1A shows a schematic diagram of a simple, paper-based force sensing cantilever. In this device, a carbon resistor is located at the root of the cantilever. When a force is applied to the beam structure, the resistor will experience a mechanical strain/stress, which then induces a change in resistance of the resistor. Measuring the change in resistance allows quantification of the applied force.

Fabrication of the Paper Device

Figure 1B summarizes the process used to fabricate the device. We fabricated paper cantilever beams by cutting chromatography paper (0.34 mm thick) using a laser cutter.

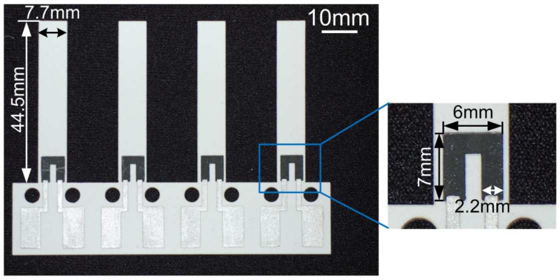

Figure 2: A photograph of an array of four devices.

We manually screen-printed carbon resistors using high-resistivity graphite ink, and contact pads using low-resistivity sliver ink [7]. We generated a stencil mask by cutting designed patterns into vinyl stencil film using a laser cutter, placed the stencil mask on top of the patterned paper cantilever beams, filled the openings of the stencil mask with graphite ink, and removed the stencil mask to form the carbon resistor. We baked the paper device at 60 °C for 20 minutes. After the drying of the graphite ink, we screen-printed another layer of silver ink to form the contact pads following the same procedure. Fabricating an array of paper-based force sensors (Figure 2) typically takes less than one hour.

Monolithic Integration of a Signal Processing Circuit onto the Paper Device

In order to convert the change in resistance of the sensor into an electrical signal (voltage), a Wheatstone bridge circuit (Figure 3A) is commonly used for signal processing in piezoresistive sensing systems. There are two ways in conventional MEMS to integrate signal processing circuits with the MEMS sensor: (i) A two-chip approach, where a MEMS device is mounted on a printed circuit board (PCB) on which the signal processing circuit is laid out; the electrical connection is achieved using wire-bonding [9]. (ii) A monolithic approach, where a MEMS device and a conventional IC signal processing circuit (e.g., CMOS) are microfabricated on the same silicon chip (e.g., CMOS-MEMS) [10]. The monolithic approach provides smaller chip footprint and much lower noise levels, but is more complicated to fabricate.

For our paper-based MEMS sensors, we developed a monolithic approach that integrated the whole Wheatstone bridge circuit with the paper-based sensor. This approach was inspired by a previous paper [11], which used paper as a flexible PCB for construction of circuits. As shown in Figure 3B, we laid out connections of the entire Wheatstone bridge circuit (including the carbon resistor R_s) by screen-printing silver ink on the base of the paper-based sensor, then gluing three surface-mount resistors (R_1, R_2, R_3) at appropriate locations, and finally 'solding' them into the circuit using silver ink. R_3 is an adjustable resistor that is used to initially balance the Wheatstone bridge.

Silanization of the Paper-Based Device

To minimize the effect of changes in relative humidity of the ambient environment on the performance of the device, we functionalized the paper surface hydroxyls with (tridecafluoro-1,1,2,2-tetrahydrooctyl) trichlorosilane vapors to render the surface of the device hydrophobic. After silanization, the surface of the device had a water contact angle of 140°.

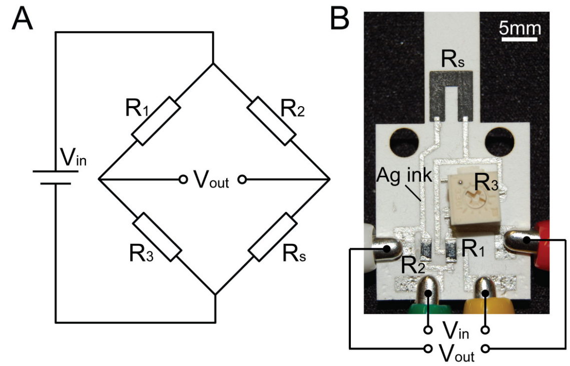

Figure 3: Monolithic integration of a Wheatstone bridge circuit with the paper-based sensor. (A) Schematic diagram and (B) photograph of the Wheatstone bridge circuit laid out on the base of the sensor.

RESULTS AND DISCUSSION

Mechanical Properties of the Paper Cantilever Beam

We first characterized the stiffness of the paper cantilever beams using a precision balance (force resolution: 1 μN), by measuring forces applied to the free end of a paper cantilever as a function of the beam deflections. The stiffness of a paper cantilever (44.5 mm long, 7.7 mm wide, and 0.34 mm thick) was determined to be 2.0±0.16 mN/mm (N=7). We also calculated the Young's modulus of the paper material using the beam equation:

$$E = \frac{4L^3 F}{\delta W H^3} \tag{1}$$

where E is the Young's modulus of the paper material, F is the applied force, δ is the beam deflection, and L, W, and H are length, width, and thickness of the paper cantilever beam. The Young's modulus of the paper material was determined to be 1.98±0.17 GPa (N=7), which is 66~86 times lower than that of silicon (130~170 GPa for single crystal silicon).

Electrical Properties of the Carbon Resistor

We measured the current-voltage (I-V) characteristic of the carbon resistors using a source meter under ambient conditions (21°C temperature and 50~60% relative humidity). All the measured resistors (N=7) revealed a linear, ohmic I-V behavior, and the resistance of the resistors was 600±190 Ω. We also investigated the temperature dependence of the carbon resistors by quantifying the temperature coefficient of resistance. We changed the environmental temperature for the paper device from 21°C (room temperature) to 80°C, and measured the corresponding resistance values of the carbon resistor. The temperature coefficient of resistance was 0.00067±0.00023/°C (N=7).

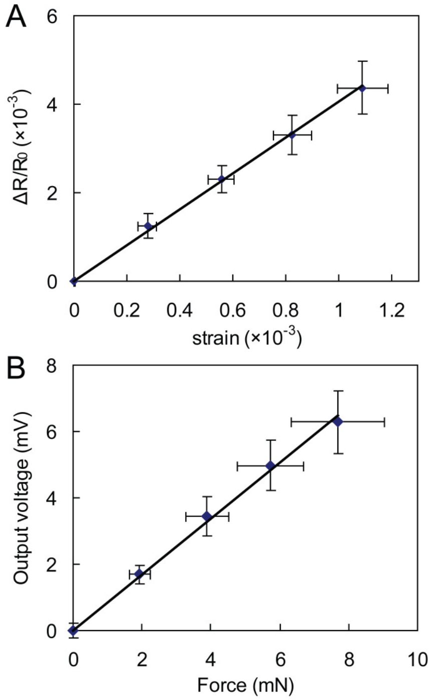

Figure 4: Calibration of the paper-based force sensor. (A) Calibration plot of the relative resistance change vs. the applied mechanical strain (N=7). (B) Calibration plot of the circuit voltage output vs. the applied force (N=7).

Calibration of the Paper-Based Force Sensor

We calibrated the paper-based force sensor using a precision balance, a LCR meter (for measuring the change in resistance), and a multimeter (for measuring the circuit output voltage). Figure 4A shows the experimental data of the change in resistance of the carbon resistor as a function of the mechanical strain applied to the carbon resistor. Based on this calibration curve, we calculated the gauge factor of the piezoresistive sensor to be 4.1. Figure 4B illustrates a calibration curve of the output voltage of the Wheatstone bridge circuit as a function of the applied force. The range of force measurement was ±16 mN, and the resolution of force measurement was 120 μN (corresponding to a voltage detection limit of 0.1 mV). The sensitivity of the sensor was 0.84 mV/mN.

Mechanical Characterization of Soft Materials

After testing the device performance, we applied the paper-based force sensor to characterizing mechanical properties of soft materials. Soft materials, such as polydimethylsiloxane (PDMS) and polyacrylamide (PAA), have been widely used for constructing micro devices [12-15] and in mammalian cell culture [16]. Mechanical properties (e.g., Young's modulus) of the soft material are important in applications where the soft material acts as mechanical components (e.g., force sensing posts [12-14] and microfluidic valves/pumps [15]) or cell culture substrates (stiffness of which affects material surface chemistry and cell behavior) [16]. Characterization of the mechanical properties

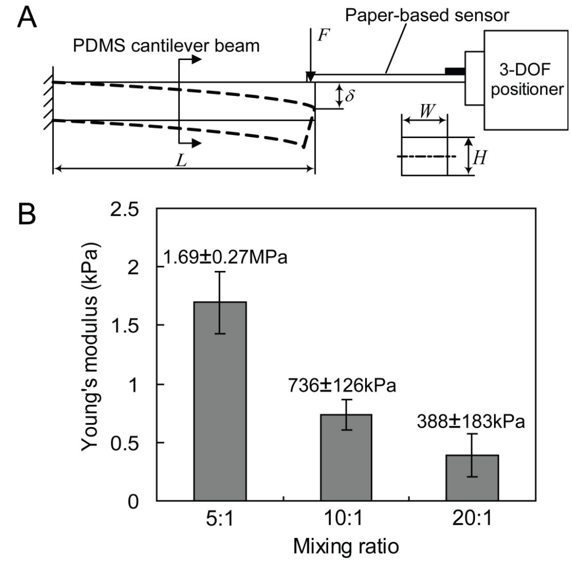

Figure 5: Mechanical characterization of PDMS materials. (A) Schematic of the system setup. (B) Experimental data of measured Young's modulus (N=7).

of soft materials is based primarily on tensile testing and nanoindentation, both of which require access to expensive equipments.

We demonstrated that our paper-based force sensor can be used as a simple tool to measure the Young's modulus of PDMS. We prepared PDMS cantilever beams by cutting appropriately sized slabs from a sheet using a scalpel, and then controlled a paper-based force sensor to deflect the cantilever beam; during deflection, we measured the applied contact forces and resultant deflections of the cantilever beam. The young's modulus of the PDMS material was calculated using Eqation (1). We tested three types of PDMS materials prepared with different mixing ratios (w/w: 1:5, 1:10, 1:20); the experimental results agree with the literature data [17].

Paper-Based Weighting Balance

We also developed a paper-based weighting balance using the same sensing principle. As shown in Figures 6A, paper-based force sensing beams were used to tether a weighting plate and measure forces due to the gravity of an object placed on top of the weighting plate. Figure 6B is the photograph (top view) of a balance prototype, where four force sensing beams are involved. We calibrated the balance by measuring the change in resistance of the carbon resistor from one sensing beam as a function of the applied weight (Figure 6C). The measurement range of the balance was 15 g, and the measurement resolution was 25 mg.

CONCLUSIONS

We explored the feasibility of fabricating MEMS sensors using paper as the structural material, and developed paper-based piezoresistive force sensors. The use of paper for MEMS construction significantly simplifies the fabrication process relative to that used with silicon and other traditional

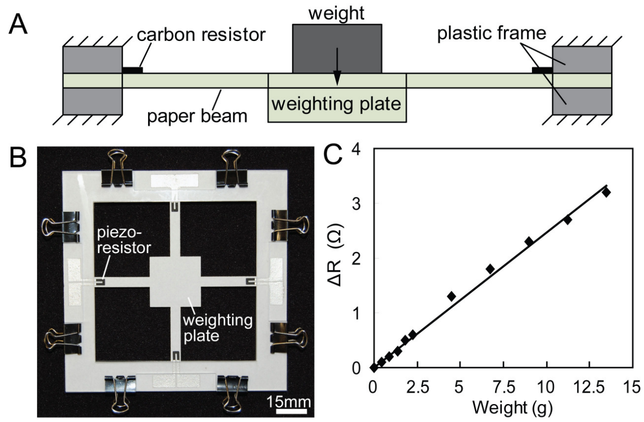

Figure 6: A paper-based weighting balance. (A) Schematic side view and (B) photograph (top view) of the device. (C) Calibration plot of the resistance change from one sensing beam vs. applied weight.

MEMS materials, and eliminates the requirement of cleanroom facilities.

The paper-based MEMS technology has four advantages: (i) It represents a simple, fast, and low-cost solution for constructing certain types of MEMS devices. (ii) Paper, as the major material for device construction, is readily available, light-weight, easy to manufacture. It can be safely disposed of by incineration. (iii) Manufacturing of paper-based MEMS devices has the potential to be fairly simple and to involve low-cost tooling; prototyping can be carried out using simple tools (a paper cutter and a painting knife), and has the potential for mass production (by automatic paper cutting and screen printing). (iv) Paper can also be used as a substrate for laying out electrical circuits, permits electrical circuits for signal processing to be readily integrated with the paper-based sensor to form monolithic paper-based chips. The paper-based sensor presented in this paper is suitable for force sensing applications that require moderate sensing capabilities and where the device cost is a major concern.

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