FABRICATION TECHNOLOGY OF PIEZORESISTIVE CONDUCTIVE PDMS FOR MICRO FINGERPRINT SENSORS

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ABSTRACT

This paper reports the characterization of piezoresistivity of Conductive Polydimethylsiloxane (CPDMS) and the corresponding fabricating process for a parylene-coated, CPDMS Micro Fingerprint Sensor (MFS) with mushroom-shaped electrodes. Gauge factor of about 7.4 was demonstrated, and the piezoresistive sensitivity was about 3×10^{-6} Pa^{-1} in the tensile test setup. The packaged MFS sensors were characterized by a pneumatic test and a nanoindentation test. We demonstrate that the fabricated device can detect pressure and force levels bellow 10 kPa and 50 µN, respectively. The use of the material and process presented in this paper offers the opportunity to realize a robust micro fingerprint sensor with low cost, low temperature process on different substrates.

INTRODUCTION

Biometrics refers to the automatic identification of a human being's physiological characteristics. Various types of biometric systems are being used for real-time identification; one of the most popular types is fingerprint recognition. Many micro fingerprint sensors (MFS), such as capacitive, thermal, pressure types, have been proposed [1]. However, the MFS with the ability to capture human fingerprints with different surface conditions (dry, wet, or dirty) still remains a real challenge.

In order to solve this problem, capacitive pressure-type MFS sensors that directly detect the topography of the finger surface were reported [2]. Each pixel of the MFS has a movable electrode which can be deflected by finger pressing. Since the capacitance becomes much smaller with reduced pixel size, the integration of the amplifying circuits underneath the pixels is therefore required. This results in significant cost increase of the fingerprint sensors. In addition, since the area of MFS must match the size of one finger, about 1:1 for touch mode or 1:10 for sweeping mode, the cost of capacitive-type MFS will not decrease with the latest microelectronics technology. Therefore, a low cost, non-capacitive, pressure-type MFS is attractive for some applications like portable electronic devices or smart cards.
During the last decade, polymers have witnessed an increased attention in the sensor research community [3]. Although the pressure-sensitive behavior of conductive polymer has been reported, most of the existing research work only focused on bulk material [4, 5]. In particular, Poly(dimethylsiloxane) (PDMS), due to its flexibility, biocompatibility and simple fabrication using soft lithography, has been applied to many bio-MEMS and microfluidic devices [6]. Conductive PDMS, i.e., mixture of PDMS and carbon black (Cabot Corporation, USA), was recently shown to be a good electrode material for micro GER valve [7], and was also reported to be used to realize an all-polymer two-axis artificial hair cell flow sensor [8].
However, in the application of pressure sensors, the use of CPDMS faces some challenges. Firstly, the resistance of a CPDMS resistor will be unstable if CPDMS can not provide good contact with the metal electrodes. Secondly, the CPDMS resistor will swell due to its porosity resulting in resistance mismatch upon exposure to a wide variety of gases and humidity [9]. To solve these problems, we propose a pair of mushroom-shaped electrodes enabling to increase the contact area as well as contact force between the CPDMS layer and the electrodes. In addition, the CPDMS resistor can be coated with a parylene thin film to ensure low moisture/chemical permeability and long-term stability.

In this paper, we demonstrate CPDMS to be an excellent piezoresistive sensor material for MFS. Because of the low Young's modulus of CPDMS, our MFS sensors can be simply prepared on a solid substrate instead of a membrane over a cavity used by their capacitive counterparts. This leads to a simple low-cost fabrication process. In addition, the proposed MFS is a piezoresistive sensor that can avoid the necessity of complicated and costly amplification circuitry required underneath most capacitive devices. Moreover, the CPDMS MFS is insensitive to human fingers' surface conditions.

MATERIAL CHARACTERIZATION

The conductive composite polymer was prepared by mixing the PDMS solution (Sylgard 184, Dow Corning, USA; ratio of the base to curing agent = 10:1) with the carbon black particles (Vulcan® XC72R, Cabot Corp., USA) to 20 %wt. Before the use of the composite polymer, it was degassed for at least 20 minutes, and then was cured for about 4 hours at 80°C.

The stress (σ) strain relationship and the piezoresistive effect of the bulk CPDMS (20% wt.) sample with the dimensions of $14\times7.3\times4.1$ mm^3 were tested in a tensile test system (Aliance RT/5, MTS Systems Co., USA) with a digital multimeter as shown in Fig. 1. In order to prevent the buckling of the sample, the CPDMS was glued by a silver epoxy between two copper plates. The pure PDMS sample with the dimension of $39.1\times10.1\times7.9$ mm^3 was also tested with this apparatus as a reference.

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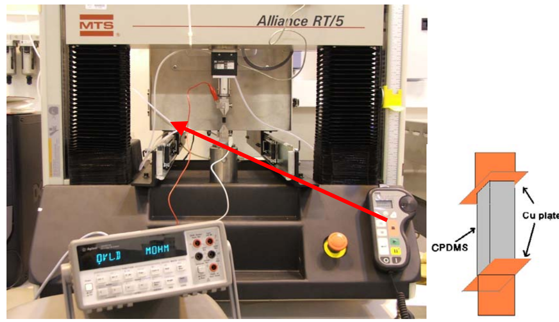

Figure 1: The electromechanical testing of the CPDMS sample using the Aliance RT/5 tensile test system with a digital multimeter.

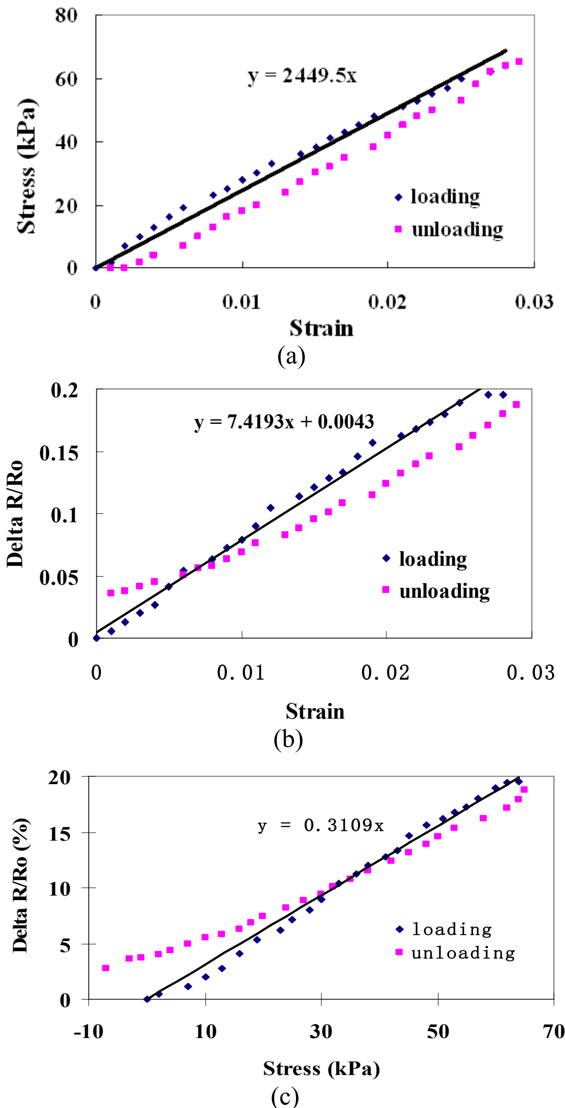

Figure 2: The electromechanical testing of the CPDMS (20% wt) during a loading-unloading cycle: (a) stress - strain relationship , (b) piezoresistivity: $\Delta R/R_0$ vs. strain , (c) piezoresistivity: $\Delta R/R_0$ vs. stress.

The Young's modulus of the pure PDMS sample was tested to be 1.2 MPa, consistent with the existing literature [6]. The Young's modulus and the gauge factor (GF) of the CPDMS were determined to be about 2.45 MPa and 7.4, respectively (Figs 2(a) and 2(b)). The GF of CPDMS is less than that of silicon (~120), but larger than the GF of commonly used metal strain gauges (2.1 for Constantan Alloy, 2.0 for Karma Alloy, and 3.6 for Isoelastic Alloy). Consider the low Young's modulus, the resultant piezoresistive sensitivity, $(\Delta R/R)/\sigma$, of CPDMS is about 3×10^{-6} Pa^{-1}, as shown in Fig. 2(c), which is about 1000 times larger than that of silicon ($<10^{-9}$ Pa^{-1}). The pressure range in which a finger presses a flat surface is 5–70kPa [10]. Thus the piezoresistive sensitivity of CPDMS can meet the requirement of a typical MFS.

DEVICE FABRICATION

A sensor array of 2×10 CPDMS was prepared on a glass substrate and coated with 1 μm thick parylene C (DiX-C, Kishimoto Sangyo Co., Japan) to minimize the environmental impact, such as moisture or gas absorption, on the sensors. Novel mushroom-shaped gold microelectrodes were electroplated to improve the adhesion of the CPDMS layer. The major process flow is illustrated in Figure 3.

First, 30 nm Ti/W (10%wt W) and 150 nm gold thin films were sputtered (Fig. 3(a)). The substrate was then spin-coated with 4μm thick AZ4620 photoresist (PR), which was used as a mold for the selective electroplating of 6 μm thick gold layer (Fig. 3(b)). Because the height of the gold layer was higher than the PR mold, mushroom-shape gold pillar was formed after the removal of the PR mold by Acetone and IPA (Fig. 3(c)). Next, the wafer was spin-coated with 6 μm thick photoresist and patterned. The micro electrodes were formed by wet etching ($KI:I_2:H_2O$= 4:1:200 for gold etching and $H_2O_2:HF:H_2O$ =2:1:50 for Ti/W etching, Fig. 1(d)).

The substrate was spin-coated with 8 μm thick photoresist to be used as a CPDMS mold. Then the CPDMS (20% wt) was squeezed on the substrate (Fig. 3(e)). A cleavage plane of a silicon wafer was used to traverse the substrate surface while maintaining direct contact with the top surface of the photoresist layer. Excessive CPDMS was mechanically removed. Later, mechanical polishing with a Chemical Mechanical Polishing (CMP) pad was used to remove the thin CPDMS residues. This resulted in patterned CPDMS in the recessed regions between the photoresist molds. The exposed photoresist was then removed by acetone and IPA. The wafers were then cured at 80°C for 4 hours. (Fig. 3(f)).

Because the CPDMS inserted into the gap of the head of the mushroom-shaped electrodes and the substrate will swell a little in the curing process, the contact force between the CPDMS and the electrodes increases. Furthermore, the contact area in the case of the mushroom-shaped electrodes is quite large than that of planar electrodes. So good contact condition and lower contact resistance are expected in the mushroom-shaped electrodes design.

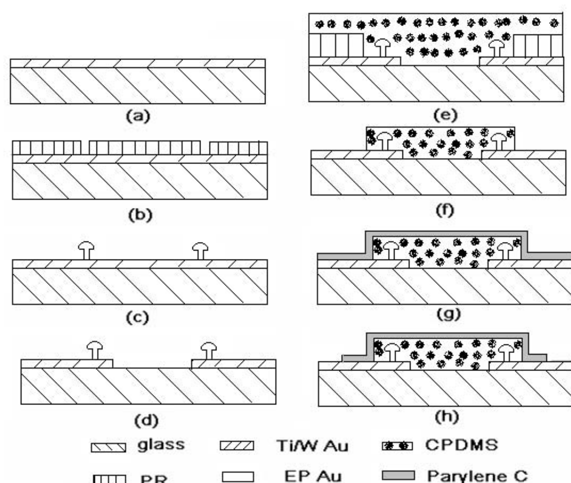

Figure 3: The process flow for the MFS device: (a) sputter Ti/W and Au electrodes, (b) pattern photoresist for Au electroplating, (c) electroplated mushroom-shaped gold electrode, (d) pattern sputtered electrodes, (e) squeeze CPDMS, (f) remove excessive CPDMS after curing, (g) deposit parylene C, (h) etch parylene layer.

A 1.0 μm-thick parylene C layer was deposited on the surface of the wafer using a parylene deposition system (Model 2010, Special Coating Systems, Inc., USA) with 0.8 gram of parylene C dimer. (Fig. 3(g)). Next, the wafer was spin-coated with 4 μm thick photoresist and patterned, and the parylene layer was etched by O_2 plasma in IPC-2000 O_2 asher (300 mT, 500 W, 100 sccm O_2 flow). Both the etching rate of the parylene and the photoresist are about 40nm/min. Finally, the photoresist was removed by acetone and IPA (Fig. 3(h)). Figure 4 shows the cross-section schematic of the sensor design and the micrographs of the fabricated devices. The dimensions of the CPDMS piezoresistor are 50×30×8 μm^3. The wafer was diced and the chip was mounted on a PCB board, and the electrodes were led out by wire bonding.

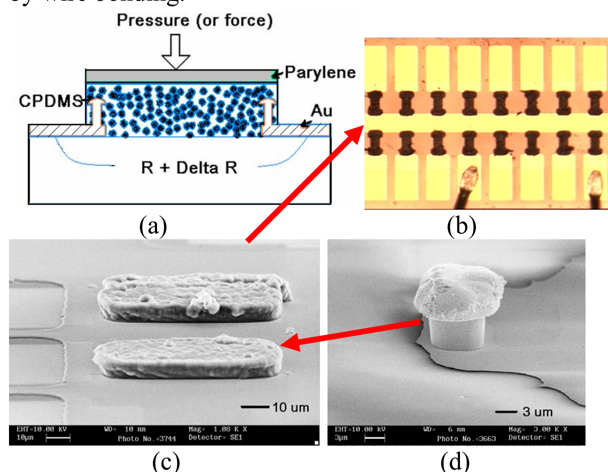

Figure 4: (a) A schematic cross-section of the MFS, (b) The photograph of a 2×10 sensor array, (c) the SEM micrograph of 2 pixels, (d) the SEM micrograph of a mushroom-shaped electrode.

DEVICE CHARACTERIZATION

Piezoresistance stability

The I-V curves of the CPDMS resistor with and without mushroom-shaped electrodes were measured with a programmable curve tracer (Tektronic 370A, Japan), and the typical results were shown in Fig. 5(a). About 30–40% CPDMS resistors with planar electrodes showed a unstable, nonlinear I-V curve, and almost all the resistance increased dramatically after a 240 min thermal cycle from 30–80 °C. While almost all the resistors with mushroom-shaped electrodes showed stable, linear I-V curve and kept contant resistance after the thermal cycle from 30–80 °C.

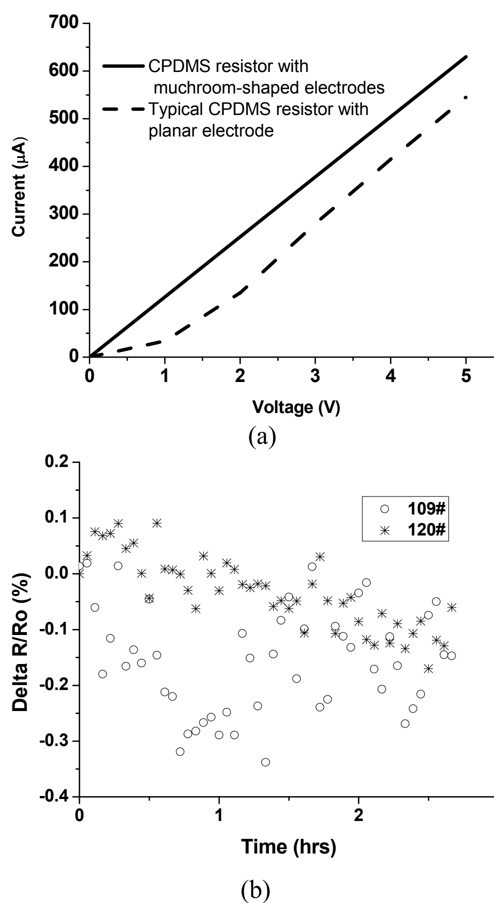

Figure 5: The piezoresistance stability testing of CPDMS: (a) typical I-V curve of the mushroom-shaped electrodes and planar electrodes CPDMS resistor. (b) The relative resistance change of the parylene coated, mushroom-shaped electrodes CPDMS piezoresistor.

The CPDMS piezoresistors were placed in an oven at 30°C and the resistance was measured at a sampling rate of one sample per second using a multimeter (Agilent 34401A) for a total duration of 2.5 hrs. The data recorded every 200 seconds is shown in Fig. 5(b). The relative resistance change of the 2 samples in 2.5 hours ranges from 0.3% to 0.5%. As the reference, the relative resistance change of a

common 10 KΩ carbon film resistor was measured, by the same apparatus in 2.5 hours, at about 0.01%.

Pneumatic testing

The MFS was tested using a controlled pneumatic apparatus with a sealed syringe. A pressure gauge (Model PG-5000-700-KPA-G, Cole Parmer Co., USA) monitored the applied pressure, and a multimeter measured the corresponding piezoresistance change. Fig. 6 shows the piezoresistance change as a function of the applied pressure. Obviously, it shows a minimum detectable pressure less than 10 kPa, close to the operating pressure range of the MFS. The resistance of the device was monitored by a digital multi-meter.

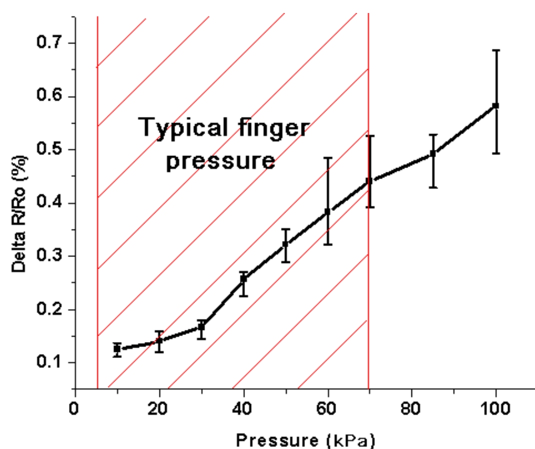

Figure 6: The piezoresistance change of a packaged MFS as a function of applied pressure.

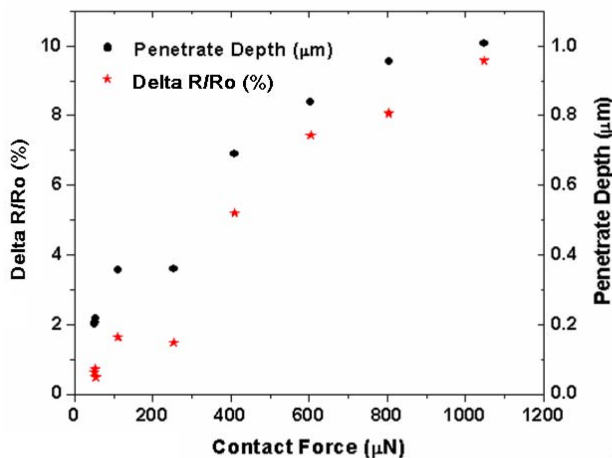

Figure 7: The piezoresistance change and penetration depth of the device (only show loading data due to limited space) as a function of applied contact force using nanoindentation technique.

Nanoindentation testing

Nanoindentation technique was also used to measure the MFS piezoresistance change under a force ranging from 50 μN to 1 mN (NanoTest^{TM}, Micro Materials Ltd., UK) using a 25μm-radius hemispherical tip. Figure 7 shows the resistance change and the penetration depth with different contact forces.

The contact force range in a pixel of MFS is 0.1–1mN [2]. From the above experimental results, the parylene-coated CPDMS MPS shows a minimum detectable resistance change under an input pressure less than 10kPa or a force less than 50 μN. Therefore, the sensitivity of our prototype is in the normal operating range of a fingerprint sensor.

CONCLUSIONS

The gauge factor of bulk CPDMS(20%wt) material was determined to be about 7.4, and the piezoresistive sensitivity, $(\Delta R/R)/\sigma$, was about 3×10^{-6} Pa^{-1}, about 1000 times larger than that of silicon. Based on these results, a CPDMS based pressure-type MFS was successfully designed and fabricated. From the pneumatic and nano-indentation testing, the parylene-coated CPDMS MFS shows a minimum detectable resistance change under a pressure and force bellow 10 kPa and 50 μN, respectively. The results indicate the dimensions and the sensitivity of the prototype can meet the requirement of standard fingerprint sensing.

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