DESIGN AND FABRICATION OF LIQUID METAL TACTILE SENSORS WITH ENHANCED SENSITIVITY AND MECHANICAL ROBUSTNESS

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ABSTRACT

Tactile sensors play a critical role in detecting both normal and shear forces. Microfluidic-channel-based piezoresistive sensors detect resistance changes caused by the deformation of conductive materials within the channel in response to applied force. To maximize deformation, soft materials, such as PDMS, with eutectic gallium indium (eGaIn) filled microchannels have been widely used. Filling the channels with liquid metal is commonly accomplished by vacuum-filling, a method that is less prone to liquid metal leakage compared to direct injection. In the fabrication of these devices, there are trade-offs between stiffness, sensitivity, and device robustness. A thicker PDMS silicon elastomer achieves robustness and prevents channel collapse during filling, but reduces sensitivity. We present novel fabrication and vacuum-filling methods that result in a highly sensitive and robust liquid-metal-filled microchannel tactile sensor that is thin and fabricated from softer elastomers.

KEYWORDS

Liquid metal (LM), eutectic gallium indium (eGaIn), tactile sensor, Dragon Skin 30 (DS-30), piezoresistive, robustness, normal and shear force

INTRODUCTION

Tactile sensors are widely used for various applications, such as robotic manipulation, prosthetic arms for amputees, and medical procedures [6], [16]. In these applications, both normal and shear forces need to be determined to enable object identification and manipulation at appropriate forces [6]. There have been a number of different sensing modalities used for tactile sensors, including piezoelectric, piezoresistive, and capacitive transducers [3]. Capacitive pressure sensors consisting of sandwich structures arranged in array form result in high spatial resolution; however, parasitic capacitances pose a challenge that limits their practical use in robotic systems [6], [11]. Piezoresistive pressure sensors do not suffer from signal crosstalk and feature convenient data collection and low power consumption [7]. In a microfluidic channel-based piezoresistive tactile sensor, a change in resistance occurs when the conductive material-filled channel is deformed in response to applied stress [16]. Channels are created in elastomers, allowing their cross-sectional area and length to change as a function of the level of stress exerted on the system [1], [14], [16]. Liquid metal (LM) are widely used conductive materials because they do not crack or mechanically fail due to large applied strains, unlike solid materials [5], [15]. Eutectic gallium indium (eGaIn) is a popular LM with low viscosity, negligible vapor pressure, high conductivity (3.4×10^4 S cm^{-1}), and low toxicity (unlike mercury) [8]. eGaIn (75% gallium and 25% indium by weight) has a melting point of 15.7 °C, so it can maintain its liquid state at room temperature [10]. Therefore, it can be easily deformed and injected into channels to create microfluidic channel-based piezoresistive sensors [2].

Researchers have explored various LM filling methods, such as direct injection, surface tension gradient, and additive and subtractive stamping methods [4]. Although each method has its advantages, there are significant challenges in LM leakage, structural complexity, requirement of electrolytes, and complicated fabrication processes [4], [10], [13]. To overcome these drawbacks, Lin *et al.*, introduced an LM vacuum-filling method for channels made in elastomer with an inlet site [13]. After applying and releasing a vacuum, channels are filled with LM at the inlet due to the pressure difference between ambient pressure and the evacuated channels [13]. Although this fabrication method can avoid LM leakage and complex device layouts by needing only a single inlet [13], it requires a relatively thick patterned elastomer to prevent channel collapse during vacuum filling. The thick substrate limits the sensor's sensitivity [12], [16]. Thinner patterned elastomer or softer materials can achieve higher sensitivity but risk channel collapse during vacuum filling. Collapsed channels prevent complete filling with LM and cause discontinuous LM channels that adversely affect sensor robustness.

To address these limitations, we introduce a novel fabrication method that eliminates the risk of channel collapse for thin microchannel structures while using LM vacuum filling. With this method, a spiral-patterned piezoresistive tactile sensor (Fig. 1a) for normal force detection is fabricated. This method achieves better robustness as compared to conventional devices by preventing collapsed channels and resulting sensor discontinuities. Furthermore, this method improves sensitivity by allowing the use of a softer elastomer (Dragon Skin 30, DS-30), which could not be employed using the conventional approach due to inevitable channel collapse.

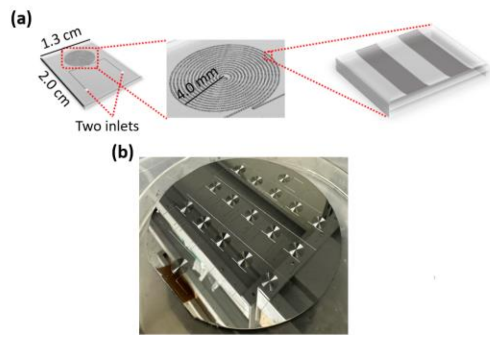

Figure 1: (a) Microfluidic channel design and tactile sensor dimensions. (b) Microfabricated silicon-based master mold.

METHODS

Microfabrication for the Master Mold

The master mold (Fig. 1b) was patterned in a lithography process. First, the silicon wafer was cleaned with Piranha solution (sulfuric acid + hydrogen peroxide in a 3:1 volume ratio) and baked on the hotplate for full dehydration (150 °C for 300 seconds). Photoresist (mr_DWL40, micro resist technology GmbH) was spin-coated onto the substrate at 1,350 rpm for 30 seconds to achieve 80 µm thickness. Then, the wafer was soft-baked on a hotplate at 50 °C for 2 minutes and 90 °C for 8 minutes. Next, it was exposed in a direct writing laser system (DWL 66+, Heidelberg Instruments) with the design file (an 80 µm width spiral pattern), and post-baked at 50 °C for 2 minutes and 90 °C for 8 minutes. Finally, it was developed for 9 minutes in photoresist developer (AD-10, Moses Lake Industries). The thickness of the mold was inspected by a stylus profilometer (Dektak XT, Bruker). After lithography, it was placed into a vacuum chamber and exposed to vapor from a trichloro (1H, 1H, 2H, 2H-perfluorooctyl) silane solution (10 drops) overnight to obtain a hydrophobic surface.

Soft Lithography and Tactile Sensor Fabrication Process

Polydimethylsiloxane (PDMS) (Sylgard 184, Dow Corning) was mixed in a 10:1 weight ratio (elastomer and curing agent) by planetary mixer (ARV-310, THINKY Corporation) at 2,000 rpm for 2 minutes. Then, it was poured onto the master mold and spin-coated at 600 rpm for 30 seconds. After spin-coating, it was placed into an oven at 80 °C for 15 minutes for full curing. For the conventional fabrication (Fig. 2a), we peeled off the fully cured patterned PDMS (~200 µm) from the mold and punched two inlets at each end of the spiral pattern using an 18 AWG blunt tip (Ind-Syr03, Brostown). We adopt a spiral pattern for the sensing geometry because it is not sensitive to shear force due to the less directional (channel length) change [18]. Flat PDMS (~500 µm) was prepared by spin coating (300 rpm for 20 seconds) on a surface-treated (hydrophobic) blank wafer. It was placed on a hot plate at 65 °C for 13 minutes for partial curing. Then, the patterned PDMS was transferred onto this PDMS gently and fully cured in the oven. Finally, it was cut and peeled from the wafer and moved to a glass slide for vacuum filling.

For the novel fabrication (Fig. 2b), the patterned layer was transferred onto the partially cured flat layer without inlets. After curing, these laminated layers were peeled off from the wafer and two holes were punched through them. Another flat PDMS layer (~50 µm) was spin-coated (1,000 rpm for 20 seconds) on a blank wafer. Then, it was placed on the hot plate at 65 °C for 2 minutes for partial curing, and the laminated structure was transferred on this layer with the patterned layer facing to the bottom. Finally, it was fully cured in the oven at 80 °C for 3 minutes. The sensor made by DS-30 was also fabricated through the same process except for the spin coating parameters (patterned layer: 30 s at 600 rpm for ~240 µm, flat layer: 20 s at 300 rpm for ~530 µm, and another flat layer: 40 s at 1,000 rpm for ~50 µm).

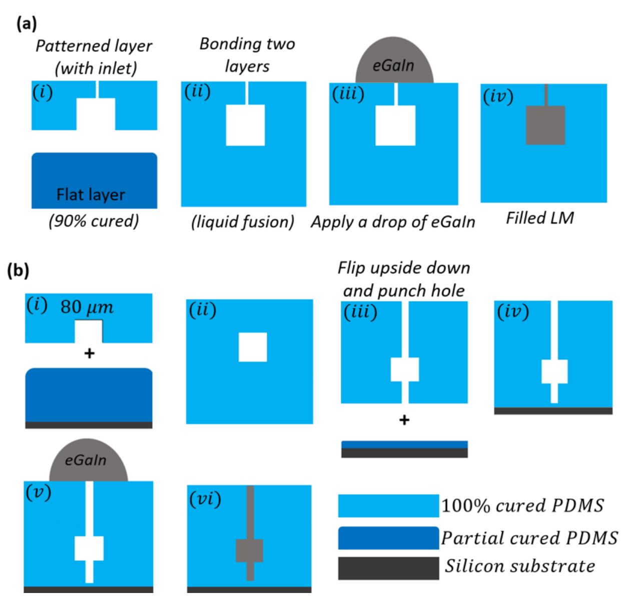

Figure 2: (a) Conventional tactile sensor fabrication process. (i) Transfer the patterned layer, which has two inlets onto the partially cured flat layer. (ii) Fully cure the joined layers. (iii) Add eGaIn onto the inlets. (iv) Fill the channel with eGaIn using a vacuum-filling process. (b) The new tactile sensor fabrication process. (i) Transfer the patterned layer without any inlets onto the partially cured flat layer. (ii) Fully cure the joined layers. (iii) Flip and punch a hole through the entire structure. Then, transfer onto another partially cured flat layer. (iv) Fully cure the joined layers. (v) Drop eGaIn onto the inlets from the flat layer side. (vi) Fill the channel with eGaIn using a vacuum-filling process.

For LM vacuum filling (Fig. 3), two droplets of eutectic gallium indium (eGaIn) (Indalloy 60, Indium Corporation) were dropped on each inlet and the structure was put inside a vacuum chamber for 20 minutes. Before opening the valve, the chamber was gently shaken to recover the shape of the LM on the inlet since a hole forms in the LM due to evacuated air from the channel. Once the valve was opened, the LM flowed into the channel. This process was repeated one more time to ensure the complete filling of the channels. After removing excessive LM, copper wire was placed onto the inlets, and additional LM was put onto the tip and covered by the same uncured polymer matching the channel material (either PDMS or DS-30) and fully cured for sealing the inlets.

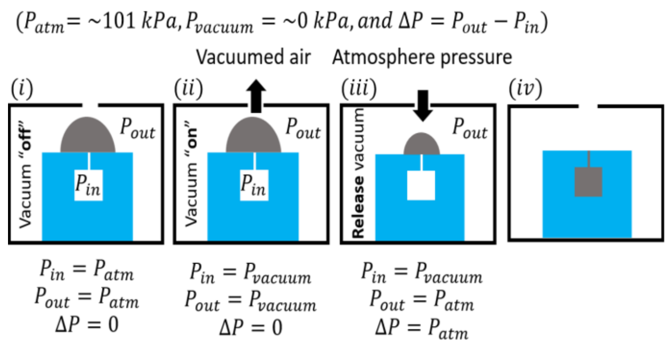

Figure 3: Vacuum filling process. (i) Before pump-down. (ii) Pumping down the vacuum chamber. After 20 minutes, all pressures are at vacuum level. (iii) After gently shaking the chamber, the valve is opened. The pressure outside the channel reaches atmospheric level, but inside the channel is still vacuum level since it is sealed with the LM. (iv). Pressure difference from (iii) fills the LM into the channel.

Robustness and Sensitivity Testing

We evaluated the tactile sensors using both imaging of eGaIn-filled channels and resistance measurements from the sensor under applied load. Images were collected using a digital SLR camera attached to a microscope. A data acquisition system was built on the optical table (PBH11105, Thorlabs Inc.), and the sensor was fixed on a customized stage (433, Newport). The Vernier micrometers (AJS100-2, SM-50, Newport) were rotated manually to apply normal stress on the sensor through the force/torque (F/T) transducer (Nano 25, ATI). The sensors made of PDMS and DS-30 were connected to a custom circuit for resistance measurement. A 5 V input voltage source was applied to both circuits using a DC power supply (UNI-PS-303, UNISOURCE) for each test. The output voltage was measured through a data acquisition card (Personal DAQ/55, Measurement Computing). Force data also was collected through a DAQ (NIUSB-6210, National Instruments Corporation). Both data could be monitored by LabView software (LabVIEW, National Instruments).

THEORY

The vacuum filling with the liquid metal requires pressure differences in both the conventional and the new fabrication methods, and it can be calculated through the Young-Laplace equation [9][12],

$$P_{Laplace} = 2\Upsilon \cos\theta \left(\frac{1}{w} + \frac{1}{h}\right) \quad (1)$$

where Υ is the surface tension of eutectic gallium indium (624 mN/m) and θ is the contact angle between the liquid metal and the side wall (~150°). Our channel has 80 µm width, w and height, h.

Thus, we require ~54 kPa minimum pressure difference to fill the liquid metal into the channel. The initial resistance of our sensor is calculated based on Ohm's law equation [10] is

$$R = \frac{1}{\sigma}\frac{L}{wh} \qquad (2)$$

Our channel has length $L = 0.27$ m, and width w=80 µm and height, h. The conductivity of the LM is (3.4 x 10^4 S cm^{-1}) [8] and the calculated value is 12.4 Ω, which is similar to the measured value (about 12 Ω).

RESULTS

We imaged tactile sensors to observe discontinuities in the LM channels, both before and after applying force to sensors. Using the conventional fabrication method, the LM appears to successfully fill the spiral channel. After moderate force is applied, LM is displaced within the channel, causing defects and persistent discontinuities (Fig 4).

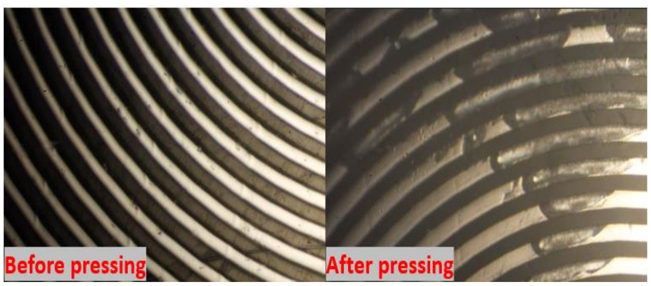

Figure 4: Comparison before and after applying pressure on the LM channel, which was fabricated by the conventional method.

We hypothesize that this failure results from channel collapse due to incomplete liquid metal filling in the channel. Incomplete filling results from partial channel collapse due to the low bending stiffness of the patterned PDMS elastomer. In addition, eGaIn may not flush the entire channel during filling due to the high surface tension of eGaIn (624 mN/m).

We employed the novel fabrication method to avoid channel collapse and increase the fraction of LM in the channels. During the filling process, the patterned elastomer is supported by the silicon wafer facing the patterned elastomer, and the LM is filled from the flat elastomer side. This flat elastomer is thicker than the patterned elastomer (see Fig. 2a, i). Due to the thick thickness (high bending stiffness) of this elastomer, partial channel collapse is prevented. In addition, this elastomer layer does not affect sensor sensitivity because its purpose is just to cover the backside of the channel (patterned elastomer). After the filling process is complete, no defects, discontinuous channels, or channel collapse have been observed even under applied force (Fig. 5).

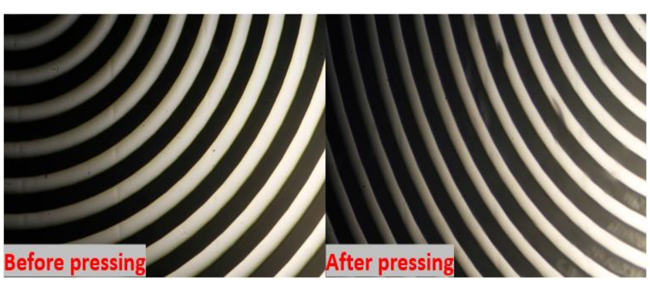

Figure 5: Comparison before and after applying pressure on the liquid metal channel, which was fabricated by the novel method.

To compare the robustness of the sensors fabricated by the conventional and the new fabrication methods, we applied a normal force to the sensor and measured the resistance. Figure 6a shows the a plot of the sensor resistance and force as as function of time. The sensor fabricated by the conventional method saturates permanently with ~22 N applied force and does not recover after the force is released. This reveals that the liquid metal no longer has a continuous electrical path through the channel. In contrast, the sensor fabricated by the new method recovers to its baseline resistance signal after the force is released (Fig. 6b), indicating that a contiguous connection with eGaIn remains.

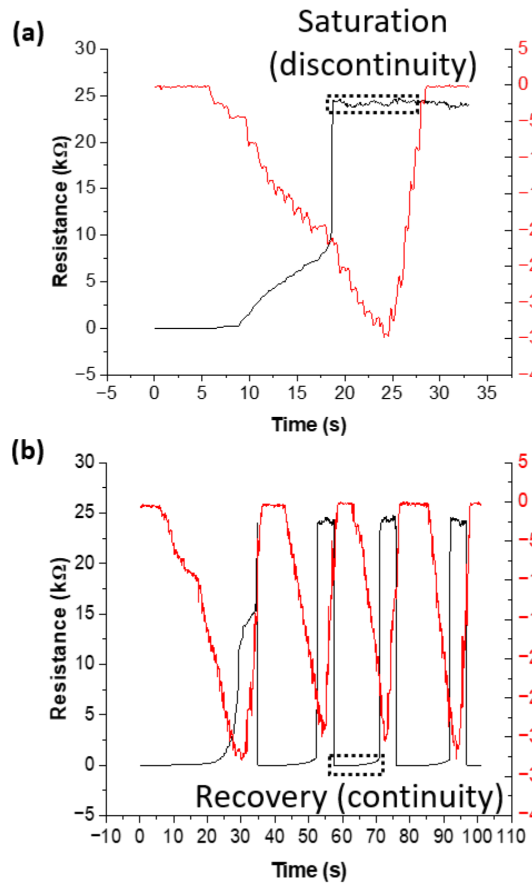

Figure 6: (a) Resistance signal from a PDMS sensor fabricated with the conventional fabrication method in response to applied forces. Channel discontinuity results in permanent sensor saturation at high applied force. (b) Signal output from a PDMS sensor fabricated through the novel fabrication method. The resistance recovers to baseline following removal of high applied force.

We observe improved sensitivity in sensors made from DS-30 compared to PDMS in the applied force range of 0 to 7 N as shown in Fig. 7. The reduced stiffness of the DS-30 sensor results in a smaller dynamic range (0~7 N) compared to the PDMS sensor (0~22 N). We observe some variability in sensor resistance measurements (Fig. 7). We also performed static measurements by applying the 5 N normal force onto the sensor for 1 hour and measuring the signal change. No signal drift was observed, which suggests that the channel is filled and there are no air bubbles for the LM to flow into.

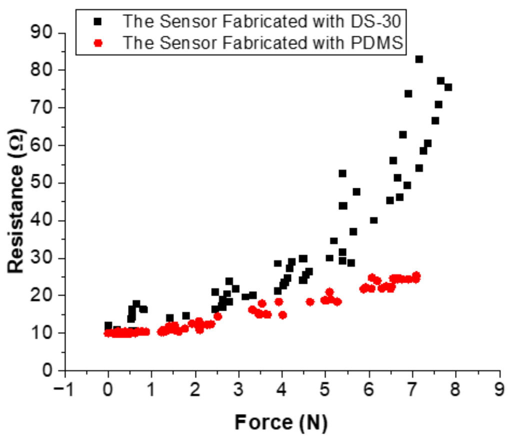

Figure 7: The improved sensitivity of the sensor fabricated with DS-30 compared to the sensitivity of the sensor fabricated with PDMS in the low range (0~7N).

SUMMARY

We present a novel fabrication method for a microfluidic-based piezoresistive tactile sensors. We describe a new approach for vacuum filling LM into microchannels that minimizes channel collapse and trapped air during the filling process. This approach improves sensor robustness by reducing instances of sensor failure after applied normal force. This new fabrictation method makes it possible to fabricate the sensor with Dragon Skin 30, which could is challenging to employ using the conventional approach due to probable channel collapse. Fabrication of sensors using a thin patterned layer of DS-30 results in improved sensitivity and recovery as compared to devices fabricated from thick PDMS. This enables the development of microfluidic-based tactile sensors with improved robustness and sensitivity that may be deployed in robotics systems for diverse applications, such as object manipulation tasks and medical procedures.

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