A robust tactile shear stress sensor derived from a bio-inspired artificial haircell sensor

Huan Hu, Chang Liu
Mechanical Engineering Department, Northwestern University
Evanston, IL, US
huanhu@u.northwestern.edu

Nannan Chen
Electrical and Computer Engineering Department, University of Illinois at Urbana & Champaign, Urbana, IL, US

Abstract— This paper reported a robust tactile shear stress sensor derived from a bio-inspired artificial hair-cell (AHC) flow sensor previously developed in our group. Not only owing excellent sensitivity and directional response, the AHC is also a versatile device with potential capability beyond flow sensing. We demonstrated here the AHC sensor is modified into a tough shear stress sensor by casting it into polymer like PDMS. This approach achieves both great sensitivity and robustness. Also it has good directional response over entire 360 degree. Moreover, with polymer’s protection, the sensor can endure people direct rub, press on it, which is a nightmare for fragile silicon devices. These good characteristics enable this shear stress sensor promising applications in robotics and virtual operating systems.

I. INTRODUCTION

There has been a great demand of high performance tactile sensors for retrieving tactile information from the surrounding. Despite the superior sensitivity, most silicon-based sensors are too fragile for such applications. On the other hand, polymer-based sensors with good robustness often suffer from poor sensitivity [1]. Our motivation is to develop a tactile shear stress sensor that is both sensitive, robust and has directional response. Kentaro developed a shear stress sensor by embedding a standing piezoresistive cantilever in Polydimethylsiloxane (PDMS) [2]. Appreciating this way of casting silicon into polymer, we demonstrated that our group’s previously developed bio-inspired hair-cell flow sensor [3] could be modified into a robust, sensitive shear stress sensor by casting it into PDMS, having a maximum sensitivity of 50mV/KPa along the cantilever length direction as well as an excellent directional response. By embedding naked silicon sensor into polymer, both sensitivity of silicon sensor and the robustness of polymer are achieved, which enables the AHC wider applications beyond flow sensing.

II. SENSING PRINCIPLE

The sensing principle of this shear stress sensor is explained in Fig. 1, when there is a shear force applied on the sensing site, it causes the shear strain of PDMS. Since the hair-cell sensor is embedded in the PDMS, the SU-8 hair and the cantilever will bend together with PDMS. The stress caused by the bending of cantilever changes the resistance of the piezoresistor. Since the piezoresistor is configured in a Wheatstone bridge, the change of resistance $\Delta R$ is further converted into a voltage signal. The final output voltage signal is obtained though a DC amplifier. By monitoring the voltage, the shear force is sensed.

III. FABRICATION

The fabrication process of the shear stress sensor is shown in Fig. 2. The first part is the fabrication of hair-cell flow sensor starting from a SOI wafer with 2-µm-thick epitaxial silicon layer on top, 2-µm-thick oxide and 300-µm-thick thick handle wafer. The SOI wafer is firstly oxidized
and patterned forming the contact windows for the doped silicon. [(Fig. 2(II))] Then electrical connection is formed by depositing 500-nm-thick aluminum on top and later on annealed in furnace to form Ohmic contact [(Fig. 2(III))]. A front etching step is followed to define the cantilever pattern [(Fig. 2(IV)]. Using a parylene coating to protect front side, back-side etching is applied with DRIE (deep reactive ion etching) to create the cavities underneath the cantilevers [(Fig. 2(V)]. After this step, SU-8 2075 (Micro-Chem, Inc.) is spin-coated on with 500RPM/min for 30 seconds to attain a thickness of 550 µm [(Fig. 2(VI)] and patterned to form the SU-8 hair on each die. Following this, the wafer is then diced up into single dies that are put into BOE for releasing the cantilever structure [(Fig. 2(VII)]. After a step of removing the coated parylene, each device is glued on a PCB board and wire-bonding is performed to make the electric connection [(Fig. 2(VIII)]. Till here, the first part of fabrication is finished. More detailed process information is referred to [1]. The second part is to cast the hair-cell flow sensor into polymer. Poly(dimethylsiloxane) (PDMS, Sylgard 184 Dow Corning Corp) is used here. After 10:1 ratio mixing up and degassing, it is slowly poured onto the hair-cell flow sensor, then heated in oven at 90 degree for 20 minutes for curing[(Fig. 2(VIV)].

![Fig. 2. Fabrication process of shear stress sensor](image)

A SEM (Scanning electro microscopy) picture of the hair-cell sensor is shown in Fig. 3. The height of the hair is 550 µm. The three cantilever-like shapes are other 3 implanted regions that form the Wheatstone bridge with the implanted cantilever.

![Fig. 3 SEM picture of a hair-cell flow sensor](image)

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![Fig. 4. Optical picture of the shear stress sensor (compared to a quarter)](image)

Fig. 4 shows the optical photo of the shear stress sensor compared to a US quarter dollar. The silicon die on top of the PCB board embedded in PDMS has a dimension of 7mm in length and 3.5mm in width.

![Fig. 4. Optical picture of the shear stress sensor (compared to a quarter)](image)

IV. EXPERIMENTS AND CHARACTERIZATIONS

The application of shear stress sensor is shown in Fig. 5. The sensor is connected to an electric box, which is further connected to an oscilloscope (500MHZ, agilent). The sensor can detect the motion of rubbing. The pattern displayed in the oscilloscope shows that the finer was rubbing the surface periodically.

For characterizing the shear stress sensor, a circular fixture is glued on the surface of the sensor, right on top of the hair. One end of a thin thread is attached to the circular fixture and the other end is pulled by weight. Dividing the weight by the area of the circular fixture, the shear stress is acquired. The final output voltage is given by an oscilloscope (Agilent DSO6104A 1GHz). Two different
kinds of tests were carried out. The 1st test is the sensitivity measurement along the cantilever length direction (maximum sensitivity direction). The 2nd test was the directional response test. Shear stress with constant magnitude but different direction was applied.

Fig. 5 An example of how the sensor can be used

Fig. 6 shows the sensor output with respect to the shear force along the direction of the cantilevers. Five runs were performed showing minimal derivation between runs. The sensor presents linear response with the sensitivity 50mV/KPa.

Fig. 6. Output signal Vout versus shear stress parallel to the cantilever (5 data sets)

Because of the cantilever structure, the sensor is most sensitive to the shear force applied parallel to the cantilever length direction. It is least sensitive to the shear force applied perpendicular to the cantilever length direction. Directional response was obtained by subjecting the sensor to a constant stress magnitude (2 KPa) at 15° increment over the entire 360°. A clear “figure 8” pattern on the polar plot (Fig. 7) demonstrates excellent directional sensitivity of the device. The maximum output is observed along the direction parallel to the cantilever and near-zero output along the direction perpendicular to the cantilever. This is very important in determining the direction of the applied force.

Fig. 7. Magnitude of output signal |Vout| versus angle between shear stress and cantilever beam (constant stress magnitude 2 KPa)

V. CONCLUSIONS

A robust shear stress sensor with high sensitivity and excellent directional response is developed by casting AHC sensor into polymer. With the protection of polymer, the sensor can be directly touched, rubbed and pressed, which reverses the sensor great potential to be used as a tactile sensor in virtual operation system and robotics.

REFERENCES

