A SIMPLE METHOD TO IMPLEMENT AND FURTHER PERFORMANCES ENHANCEMENT OF THE SHEAR FORCE SENSOR

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ABSTRACT

This study reports a simple method to design the shear force sensor using the SOI wafer with polymer filler (PDMS). The shear force sensor contains three sensing units: two cantilevers with piezo-resistors are the sensing units to detect shear force in two orthogonal directions and the central membrane with piezo-resistors is the sensing unit to monitor the normal load. The polymer filler serves as the interface layer for force transmission and the protection layer for suspended sensing units. The performance of the shear force sensor can be improved by varying the cavity size of sensing cantilevers. Measurements indicate that the sensitivity increases for 4-fold (from 0.039%/kPa to 0.17%/kPa) as the cavity size $W_{cavity} \times L_{cavity}$ increases from 300μm×550μm to 700μm×1350μm. This study provides a simple approach to both the design and process to change performances of the shear force sensor.

INTRODUCTION

Tactile sensors for normal/shear force detection have various applications in recent years, such as the ones for robot hands. Normal force detection in robot hands is essential to distinguish whether the contact happens and can be further implemented with arrays to obtain force distribution where the shape of an object can be detected. The membrane is a robust and straightforward structure to detect normal force [1-2]. To acquire the detailed loading condition and prevent slippage between the robot hand and the object, tactile sensors with shear force sensing capabilities play an important role. Moreover, the shear force could introduce unsymmetrical deformation of the membrane. The different deformations on opposite sides of the membrane are exploited to determine the shear stress [3]. However, it is challenging to detect the small deformation caused by the shear force.

Various approaches have been investigated to improve the shear force sensing capability. The cantilever beam is another simple and promising structure as the sensing element and is extensively employed in tactile sensors [4-7]. However, it remains challenging to apply cantilever for shear force detection. The approaches to lift up the sensing cantilevers [4-5] or additional assembled structure can enhance shear load detection, yet complicated fabrication and assembly processes are required [6].

This study presents a piezo-resistive type shear force sensor consisted of three sensing units, as in Fig.1. The cantilevers respectively arranged in two orthogonal directions (x-axis and y-axis) are employed as two sensing units for shear forces detection. Moreover, the membrane is exploited as the sensing unit for normal load detection. The

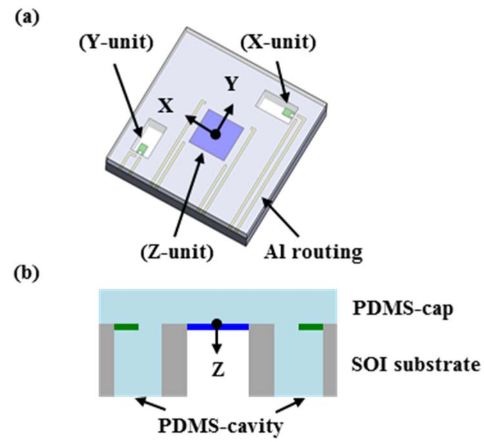

Figure 1: Schematic of the shear force sensor with three sensing units, (a) bird's eye view, and (b) cross-section view of the chip.

SOI wafer is used to implement the presented designs. The polymer filler acts as the interface layer for the transmission of force as well as the protection layer for suspended sensing units, which is similar as [4]. In this design, the shear force detection performance is improved by varying the size of the cavity size of sensing cantilevers. The sensing cantilever and the cavity are easily defined and implemented by using the SOI wafer and existing micro fabrication processes. No special fabrication and assembly processes are required.

DESIGN CONCEPT

Fig.1 illustrates the schematic design of the proposed shear force sensor. The polymer (PDMS) is employed as the filler to partially encapsulate the chip. Thus, the polymer acts as the interface layer to transmit the external loads and to protect the fragile suspended sensing structures as well. In Fig.1a, the shear force sensor consists of three sensing units: the shear forces in two orthogonal directions are respectively detected by the X-unit and Y-unit, and the Z-unit is for normal load monitoring. The Al routings on chip enables the bonding area to be distant from the force sensing area. As shown in Fig.1b, the cantilevers are exploited in X-unit and Y-unit as the sensing structures. The cantilever suspended above a bulk micro-machined cavity is protected by the encapsulated polymer. Moreover, the membrane is employed as the sensing structure for Z-unit. The membrane is not fully protected by the PDMS as limited by fabrication processes.

Fig.2 shows the principles of force sensing in the present device. The force deforms the polymer and further bends the sensing structures to cause resistance change of piezo-resistors. In Fig.2a, the boron doped piezo-resistors are placed at the beam end. As the shear force is applied in the

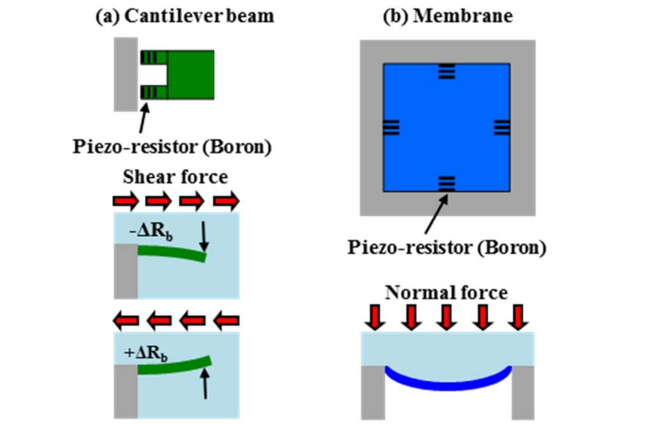

Figure 2: Sensing mechanism of the shear force sensor, (a) the cantilever beam bends in reverse directions for opposite shear force sensing, and (b) the membrane bends downwards for normal force sensing.

direction from anchor to tip of the cantilever, the beam bends downwards. Whereas, the cantilever bends reversely by the shear force in opposite direction. The deformation induces maximum surface stresses at both ends of the beam, and the change of magnitude can be picked up by the resistance change of piezo-resistors (ΔR). In Fig.2b, the boron doped piezo-resistors are placed on the four sides of the rectangular/square membrane. As the normal force is applied, the membrane bends downwards and induces maximum stresses near the edges of the membrane, which can be picked up by the resistance change of the piezo-resistors. Note that the four piezo-resistors are ideally designed to build a full-bridge circuit.

In this study, the characteristics (such as sensitivity and sensing range) of the proposed shear force sensing units can be modulated by varying the size of PDMS-cavity (W_{cavity} or L_{cavity}) and the beam length (Fig.3a). The concept is supported by the simulations in Fig.3b. For a 25kPa shear load, the results indicate the average stress on piezo-resistors (i.e. sensitivity) increases from 3.9MPa to 36.4MPa as cavity size ($W_{cavity}\times L_{cavity}$) increases from 300µm×550µm to 700µm×1350µm with fixed sensing beam length L_{beam}=280µm. Simulations in Fig.3c also show the variation of average stress versus L_{beam} (150µm×700µm, cavity size is fixed as 500µm×1350µm). In short, simulations demonstrate that the proposed shear force sensor could be further improved by modulate the geometry of cantilever and cavity respectively in Fig.3b-c. Moreover, the modulation of PDMS-cavity is more effective approach for sensitivity enhancement.

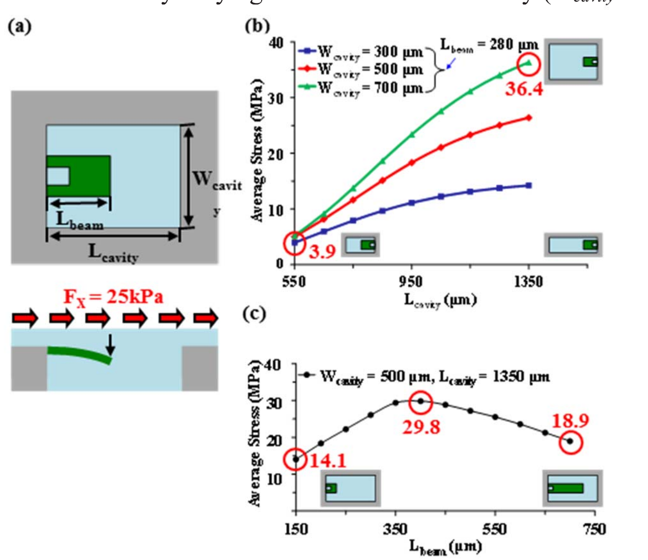

Figure 3: Simulation results, (a) design model, (b) the average stress vs. ($W_{cavity}\times L_{cavity}$), and (c) the average stress versus L_{beam}.

FABRICATION

The fabrication process of the shear force sensor is shown in Fig.4. Firstly, the SiO_2 was grown and patterned as the hard mask for implantation. Boron ions were implanted into SOI wafer as piezo-resistors (lightly doped boron) and electrical connections between piezo-resistors (heavily doped boron), as in Fig.4a. The wafer was annealed to activate boron ions and then the SiO_2 was grown again. The SiO_2 layer serves as an isolation layer. After exposing the heavily boron doping layer, Al film was deposited to connect the electrical signals below isolation layer, as in Fig.4b. The device layer was then patterned by DRIE to define the sensing structures, as shown in Fig.4c. The backside Si DRIE was implemented to define the cavity size of sensing units as illustrated in Fig.4d. As in Fig.4e, the chip level device was wire-bonded on PCB. After that, the chip on PCB was filled with PDMS by molding process in an acrylic mold, as in Fig.4f.

Fig.5 shows typical fabrication results. The SEM micrographs in Fig.5a-b show the front-side and back-side views of a fabricated chip before PDMS filling (in Fig.4d). The cantilever beam and the membrane are properly defined and proofed suspended by the checks of dynamic behavior. The footprint of the sensor chip is about 4mm×4mm. Fig.5c shows the integration of the sensor on PCB after the molding process for load tests. Due to the nonstandard demolding

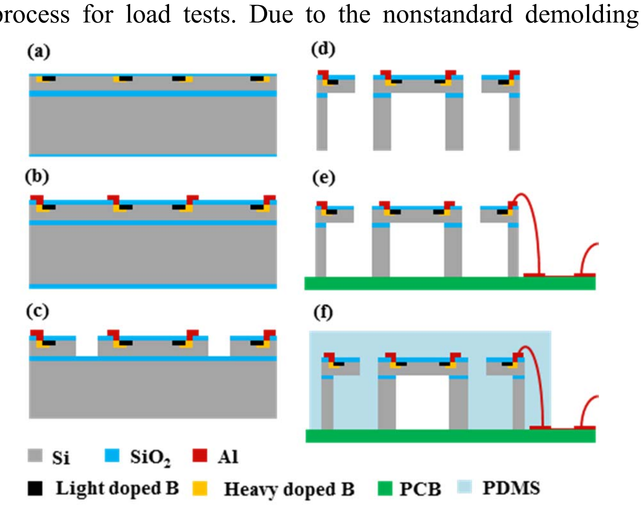

Figure 4: Illustrations of fabrication processes.

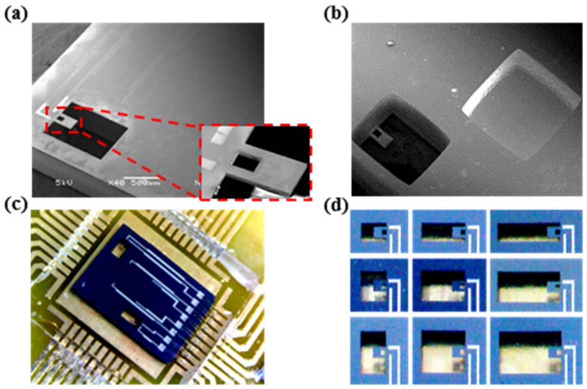

Figure 5: Fabrication results, (a-b) SEM micrographs of view from top and backside before PDMS molding process, (c) integration on PCB after PDMS molding process, and (d) various sizes of the PDMS-cavity on different chips.

process by knife cutting, there are fragments of PDMS on the edges of the PDMS-cap and surface of PCB. The total sensor size is 8mm×8mm, including the chip and the external PDMS. Fig.5d shows chips with different sizes of PDMS-cavities for tests.

MEASUREMENT RESULTS

This study has measured the characteristics of the shear force sensor versus loading forces. Furthermore, the modulation of shear force sensitivity by varying the size of PDMS-cavity was also characterized. Fig.6 shows the measurement setups respectively for normal/shear force tests. The sensor was fixed to the position stage and the micro force gauge with 50mN resolution was used to apply load on the sensor, after specifying a displacement on the position stage. In Fig.6a, the contact head of force gauge moved toward the surface of the sensor to apply normal forces ranging 0-156.25kPa for the characterization of Z-unit. In Fig.6b, the head of the force gauge moved horizontally along the surface of the sensor under a preloading normal force of 31.25kPa (monitored by the Z- unit on chip) to introduce shear forces of 0-12.5kPa via friction. Note that the Polypropylene (PP) adjustment tube and acrylic pillar is designed to enable the contact head to tightly attach to the surface of sensor. Fig.6c displays the instruments for the recording of sensing signals. The resistance change of piezo-resistors (ΔR_b) on cantilever beams were measured by LCR meters. In addition, the four piezo-resistors on the membrane formed a full-bridge circuit. The power supply was used to offer the voltage bias (V_{in}=5V) and the source meter was employed to record the voltage output (ΔV). The ratio of resistance change of the piezo-resistors ($\Delta R_m/R_m$) is thus determined by the measured fractional voltage change $\Delta V/V_{in}$.

Fig.7 shows the measurement results characterized from a single chip with a specific PDMS-cavity size of W_{cavity}=500μm, and L_{cavity}=950μm. The results in Fig.7a-b indicate that the sensitivity of shear force sensors are 0.084%/kPa (x-axis) for the X-unit and 0.041%/kPa (y-axis) for the Y-unit. Measurements indicate that the sensitivity of X-unit is two-fold higher than that of Y-unit. However, according to the simulation, these two sensing units has the same sensitivity. The difference may come from the process deviations and the unsymmetrical geometry of these two units. These issues will be further investigated to improve the performances of sensors. Due to the full-bridge circuit design, the shear force has very small crosstalk on the Z-unit. Furthermore, the stiffness ratio of cantilevers reduces the crosstalk between the X-unit and Y-unit. Fig.7c shows the normal force induced resistance change detected by the central membrane. The measured sensitivity is 0.057%/kPa.

Fig.8 shows the variation of sensing signals for different sizes of the PDMS-cavity. Measurements in Fig.8a-b depict the $\Delta R/R$ (in absolute value) varying with x-axis shear force at different W_{cavity} and L_{cavity}. The sensitivity increases from 0.049%/kPa to 0.121%/kPa as W_{cavity} increases

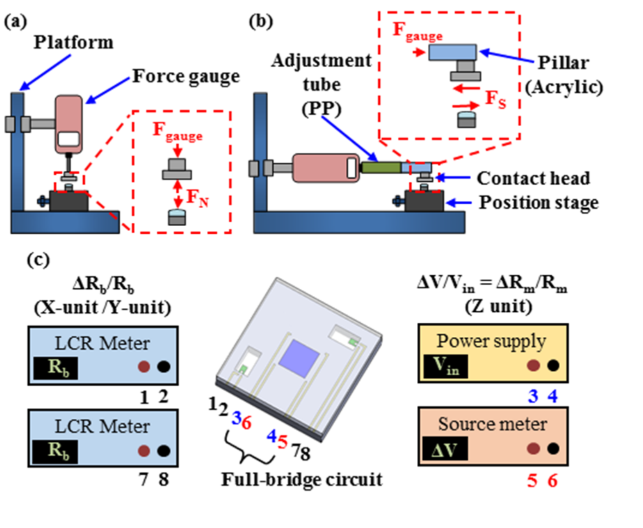

Figure 6: Measurement setups for the loading tests on sensor, (a) normal force test, (b) shear force test, and (c) I/O signals and the related instruments.

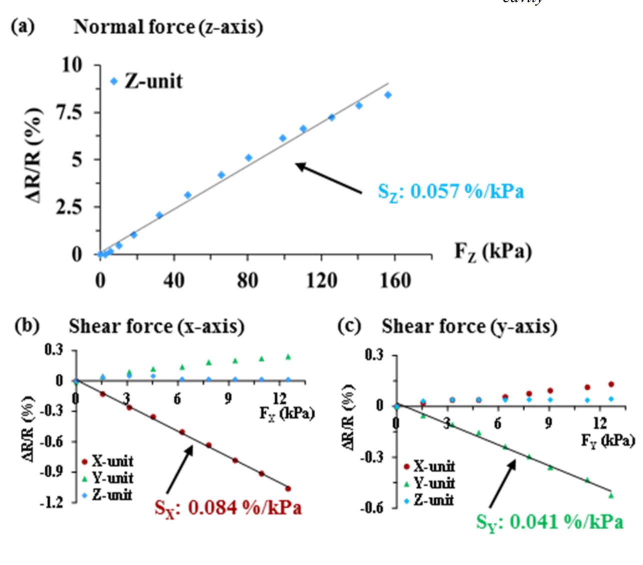

Figure 7: Characterization of the sensor (W_{cavity}= 500μm and L_{cavity}=950μm), for (a) normal force, and (b-c) shear forces respectively in x-axis and y-axis.

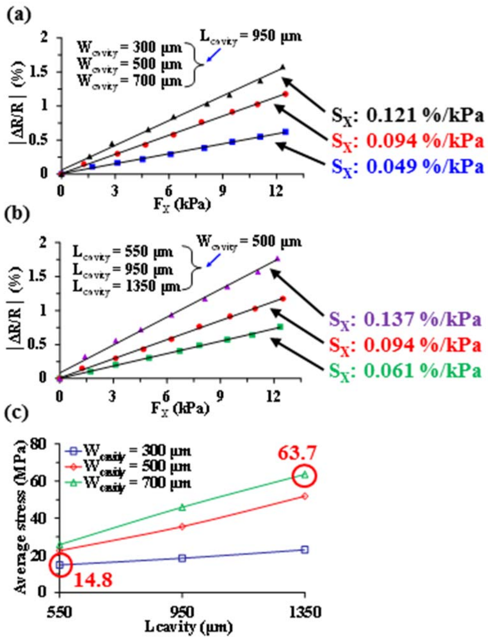

Figure 8: Compared results (under shear force in x-axis) by changing (a-b) W_{cavity} and L_{cavity} of the cavity, and (c) extracted average stress (under 25kPa shear load in x-axis) versus various sizes of the cavity.

from 300μm to 700μm (L_{cavity}=950μm), and increases from 0.061%/kPa to 0.137%/kPa as L_{cavity} increases from 550μm to 1350μm (W_{cavity}=500μm). Based on the measurements, the calculated average stress (under 25kPa shear load in x-axis) versus sensors of different cavity sizes is available in Fig.8c. In short, as the ΔR/R is measured, the stress (σ) is extracted from,

$$\pi\sigma = \Delta R/R \tag{1}$$

where π the piezo-resistive coefficient determined by the doping concentration on the piezo-resistors. The trend agrees reasonably with the prediction in Fig.3b. However, the stress variation with cavity size has decreased from a 9-fold improvement in the simulation (3.9MPa→36.4MPa) to a 4-fold improvement in the experiment (14.8MPa→63.7MPa).

CONCLUSIONS

In this study, a silicon-based shear force sensor with three sensing units has been proposed and implemented on SOI wafer. The sensing units consist of suspended deformable Si structures with embedded piezo-resistors. The PDMS polymer filler is used to encapsulate and protect the suspended Si structures. Thus, the force is transmitted through PDMS-cap to the sensing units and then induce stresses and resistance changes on piezo-resistors. The characterization from a single chip (W_{cavity}=500μm, L_{cavity}=950μm) show that the sensitivity of the specific fabricated sensor is 0.084%/kPa for X-unit, 0.041%/kPa for Y-unit and 0.057%/kPa for Z-unit. Measurements also indicate that the sensitivity has been improved or 4-fold by varying the PDMS-cavity. Such improvement was contributed by the variation of the cavity sizes (W_{cavity}×L_{cavity}) from 300μm×550μm to 700μm×1350μm. In summary, this study demonstrated a simple approach to design and fabricate the shear stress sensors. Moreover, the characteristics of the shear stress sensor can be easily modulated by varying the cavity size on Si substrate.

ACKNOWLEDGEMENTS

This project was support by the ministry of science and technology of Taiwan under grant number MOST 104-2221-E-007 -016 -MY3, MOST 105-2221-E-007 -026 -MY3, and MOST 105-2622-8-007 -006 -TE3. The authors would also like to appreciate the Center for Nanotechnology, Materials Science and Microsystems (CNMM) of National Tsing Hua University, the Nano Facility Center (NFC) of National Chiao Tung University and the National Nano Device Laboratory (NDL), in providing the fabrication facilities.

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