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A Ring-Shaped Tri-Axial Force Sensor for Minimally Invasive Surgery

Beibei Han,Yong-Jin Yoon, Muhammad Hamidullah, Angel Tsu-Hui Lin, andWoo-Tae Park

***Abstract*—**This paper presents the design of a ring-shaped tri-axial fore sensor that can be incorporated into the tip of a guidewire for use in minimally invasive surgery (MIS). The designed sensor comprises a ring-shaped structure located at the center of four cantilever beams. The ringdesign allows surgical tools to be easily passed through which largely simplified the integration process. Silicon nanowires (SiNWs) are used aspiezoresistive sensing elementsembeddedon the four cantilevers of the sensor to detect the resistance change caused by the applied load.An integration scheme with new designed guidewire tip structure having two coils at the distal end is presented. Finite element modeling has been employed in the sensor design to find the maximum stress location in order to put the SiNWs at the high stress regions to obtain maximum output. A maximum applicable force of 5 mN is found from modeling. The interaction mechanism between the designed sensor and a steel wire has been modeled by FEM. A linear relationship between the applied load on the steel wire and the induced stress on the SiNWs were observed.

***Keywords*—**Triaxial MEMS force sensor, Ring shape, Silicon Nanowire, Minimally invasive surgery.

I. Introduction

MINIMALLY Invasive Surgery (MIS)has been widely practiced in hospital over the last century because of its numerous advantages over traditional open surgery, such as reduced postoperative pain, shorter hospital stays and periods of disability, which is cost-effective for both hospitals and patients[1].However, despite rapid development of MIS techniques it was still limited by a number of unsolved problems among which the lack of force feedback iscrucial.Similarly, in the catheterization procedures, such as cardiovascular and thoracic interventional procedures, which are performed in a minimally invasive mannerto treat tissues and organs by employing catheters and guidewires, the need of force sensationare particularly importantas the surgeons totally lost the force sensation while theguidewire/catheteris interacting with blood vessels or tissues. Sometimes the blockage of the vessel lumen makes the operation even more challengeable.

Beibei Han, Muhammad Hamidullahand Angel Lin Tsu-Hui, are with theInstitute of Microelectronics, The Agency for Science, Technology and Research (A*STAR),11 Science park road, Singapore 117685 (phone: +65-93906297;E-mail: bhan1@e.ntu.edu.sg, muhammad@ime.a-star.edu.sg, linta@ime.a-star.edu.sg).

Beibei Han and Yong-Jin Yoonarewith School of Mechanical &Aerospace Engineering,Nanyang Technological University, 50Nanyang Avenue, Singapore 639798 (E-mail: yongjiny@ntu.edu.sg).

Woo-Tae Park is with Department of Mechanical and Automotive Engineering, Seoul National University of Science and Technology, Seoul, Korea. (E-mail: wtpark@seoultech.ac.kr).

So far the surgeons perform the catheterization procedures mainly with the assist of imaging techniques, such as X-ray fluoroscopyand Magnetic Resonance Imaging (MRI)to visualize the autonomy of patient and tract the guidewire/catheter. However, as an essential tool used in the catheterization procedures, the X-ray fluoroscope has obvious drawbacks such as poor soft tissue visualization and exposure to radiation which is harmful to both patients and physicians [2].To overcome these disadvantages, the MRI technique was developed with excellent visual information andlessens the radiation dose[3].However, these techniques could not provide sufficient information to detectthe interaction between soft tissue and guidewire/catheter. In order to detect the tool-tissue interaction and avoid imposing extra force, force sensors can bemounted on the surgical toolsduring the interventional procedures. Microelectromechnical systems (MEMS) have enabled the possibility of fabricatingminiaturized sensors. Recently various types of MEMS force sensors have been reported for use in MIS with the purpose to provide force feedback[4]–[13]. Especially some are developed for guidewire/catheter related applications[14]–[18]. However, most of the reported force sensors that have been developed for MIS cannot be directly used inguidewire applications because of their incompatible mechanical structures. In this paper,a ring-shaped tri-axial force sensor to be mounted at the tip of aguidewireis reported. The developed sensor has a ring-shaped structure at the center that can be integrated on the distal tip of the guidwire by passing through the hollow core. Comparing with previous assembly arrangementsreported in[13][19][20], the ring-shaped configuration is much simpler and easier to be integrated with circular shaped surgical tools.This assembly configuration minimizes the bending artifacts as it is directly integrated on the distal tip of the guidewire whereas most of the reported sensors developed for guidewire applications are mounted in a recess in the core wire.The output signal from the sensor is affected not only by the bending of the tip of guidewire itself but also the change in the physical environment surrounding the sensor[19].

II. Sensor design

A. Sensor Design

The sensor design is inspired by the requirement of mounting a force sensor on the tip of a movable core guidewire to provide force feedback during catheterization procedures. Based on the core wire configuration at the distal end, standard commercial guidewirecan be mainly divided into two different types, fixed core guidewire and movable core guidewire [21]as shown in Fig. 1.

Generally a guidewire comprises a distal tip, a core wire, a coil, and the cover. The fixed core guidewire has one single core wire from the proximal end to the distal tip of the guidewire which will enable direct torque transmission from proximal end to the tip. The moveable core guidewirehas two separated core wires which is more flexible and steerable than the fixed core guidewire. The dimensions and other properties of the guidewires can vary considerably based on the type of procedure being performed and the anatomy of patients. In the conventional design, the outer diameter of the guidwire is ranged from 240µm to 1mm whereas the core wire has a diameter ranged from 50µm to 200µm.

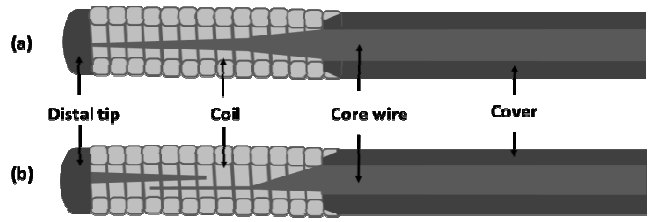
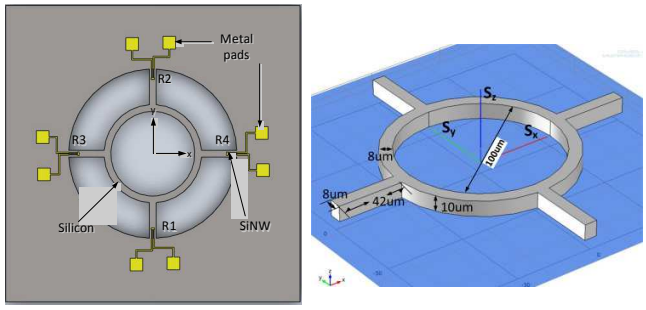


Fig. 1Standard commercial guidewire designs, (a) fixed core guidewire(b) movable core guidewire

In order to be integrated on the tapered core wire on the distal end, thedesigned senor should be of a small size less than 1 mm. The sensor must be capable of measuring forces in both normal and shear directions.High sensor resolution is also required to detect small changes in force and displacement with good linearity and low hysteresis. The designed sensor shall be integrated on the movable part of the core wire and located inside the coil. According to these requirements, a ring-shaped tri-axial force sensor has been designedas shown in Fig. 2.



(a) (b)

Fig. 2(a) Schematic of the ring-shaped force sensor design (b) Dimensions of the sensor structure: beam 42 µm × 8µm × 10 µm, inner ring diameter 100 µm, and outer ringdiameter 116 µm

The designed sensor as shown in Fig. 2 (a)consists of a suspended ring-shaped structure located at the center and four suspended cantilever beams whose axes areperpendicular to each other. The movable tip of the core wire would pass through the ring structure to be integrated with the sensor and acts as a force transmission element. Single crystalline Silicon nanowires (SiNWs)are embedded at the end of each beam as piezoresistive sensing material because of its high gauge factor [22]. When an external force is applied on the structure, the ring deforms and the resistances of SiNWs changedue to the induced strain.

The resistance changes can be measured by an additional electrical circuit. The dimensions of the sensor have been identified according to the structure dimension of guidewire where the force sensor is targeted to be integratedwith.The overall dimension of the designed sensor should not exceed the inner diameter of the coil. The diameter of the inner ring should be larger than the diameter of the movable core wire. A finite element analysis was carried out to optimize the critical structural parameters of the sensor, such as the inner and outer diameter of the ring, and the cantilever length, width and thickness. Finally, as shown in Fig. 2 (b), the diameter of the inner ring is designed to be 100µm and thediameter of theouter ring is designed to be 116µm. The cantilever beam has a size of 42 µm× 8µm ×10µm in length, width, and thickness respectively. The sensing area including cantilever beams is 200µm×200 µm whereasthe total area of the sensor with metal pads is 400µm×400 µm.

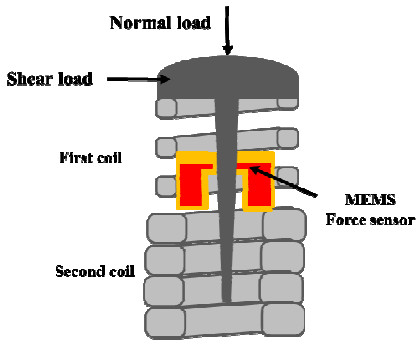


Fig. 3 Illustration of movable core guidewire with integrated MEMS force sensor

The integration scheme of the designedsensor and the movable core guidewire is illustrated in Fig. 3. A two coil structure has been designed with the purposeofinducing a differential displacement between the core wire and the coil to lead the ringdeformation. The sensor is to be integrated with the movable core wire which is connected with the distal tip and located in the first coil. When external force applied at the end of the guidewire, displacement differences between the distal tip and the coil will induce adeformation of the sensor structure. The spring stiffness of the two coils can be appropriately designed to limit the displacement of the ring in asafety range such that the robustness of the sensor can be guaranteed.

B. Sensor Principle

When an external force is applied on the sensor, the structureis deformedandstrainis induced. The relationship between the applied force and the ring displacement is as following:

$$F = K_e \Delta x \quad (1)$$

where$F$ is the applied force, $K_e$is the equivalent spring stiffnessof the sensor structure, and Δx is the ring displacement.

The piezoresistors change their resistance due to the ring displacement and the induced strain, which can be measured from the metal pads. The sensitivity of piezoresistors can be obtained by the following equation[24].

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \quad (2)$$

where R is the resistance without applied stress, ΔR is the resistance change with applied stress, π and σ represent the piezoresistive coefficient and stress respectively, and the subscripts l and t refer to longitudinal and transverse components.

Referring to Fig. of the labels of four piezoresistors, the sensitivity is defined as following.

$$S_x = \left(\frac{\Delta R}{R}\right)_x = \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}$$
$$S_y = \left(\frac{\Delta R}{R}\right)_y = \frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} \quad (3)$$
$$S_z = \left(\frac{\Delta R}{R}\right)_z = \frac{\Delta R_1}{R_1} + \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} + \frac{\Delta R_4}{R_4}$$

where S_x, S_y, and S_z are the sensor sensitivities in the X-Y-Z directions respectively. When shear force is applied, the opposite piezoresistors such as R1 and R2 will experience opposite strain (i.e. R1 will experience tensile strain whereas R2 will experience compressive strain, or vice versa). When normal loading is applied, the resistance of all four piezoresistors will have the same sign of strain (either tensile or compressive) and the Z axis sensitivity is defined as the total resistance change of all four piezoresistors.

III. FEM Modeling

A. FEM Modeling of Ring Sensor

A commercial finite element analysis tool, COMSOL, was used to study the mechanical behavior of the structure under various applied load conditions. The material properties used in the modeling were obtained from reported literature as shown in table 1.

In order to find the location of the maximum sensitivity to put the piezoresistors, regions of highest stress on the beams were identified by finite element modeling (FEM) as shown in Fig.. When normal force is applied on the top surface of the ring, the sensor beams bend downward and the maximum stress is found at the bases of the beams. SiNWs are placed at these high stress regions to obtain maximum piezoresistance output. The maximum stress at the SiNWs must not exceed the yielding stress of single-crystalline silicon, the value of which is around 300 MPa. From the simulation, the applicable force range was found to be 0 to 5 mN to avoid fracture of the sensor. The load at the end of one cantilever beam is also analyzed. The stress field and simulated strain with a prescribed 1 μm displacement load Dz is presented in Fig. . The load is applied at the junction area of a beam and the ring. The obtained stress and strain are linearly proportional to the applied load.

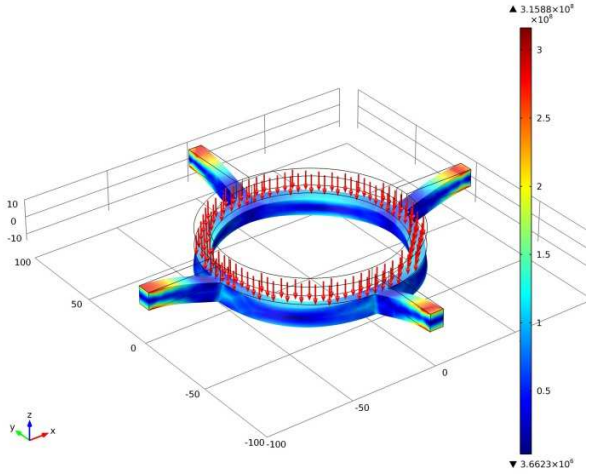
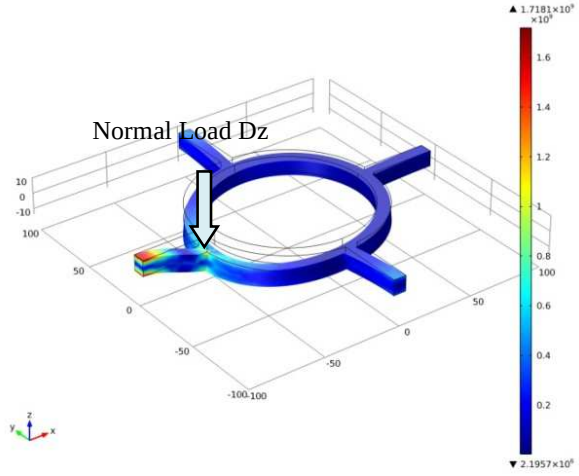
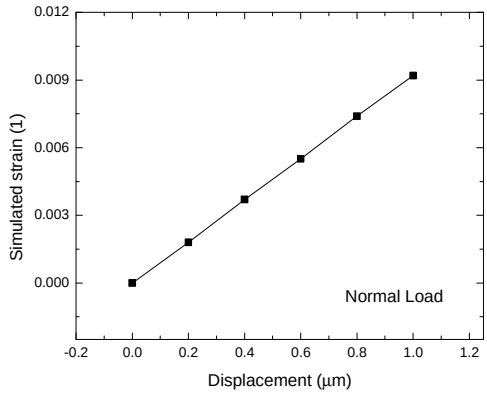


Fig. 4 COMSOL modeling result showing the von Mises stress field of the ring structure under 5mN force load applied in the z-direction.



(a)



(b)

Fig. 5 (a) Von Mises stress field of the sensor in response to 1μm prescribed displacement loaded in the z direction. (b) Simulated strain versus displacement.

TABLE I
MATERIAL PROPERTIES FOR MODELING

Material	Young's Modulus	Poisson Ratio	Density
Silicon	169GPa	0.278	2330 Kg/m^3
Steel	200GPa	0.33	7850 Kg/m^3
Epoxy	3.5GPa	0.069	1250 Kg/m^3

B. FEM Modeling of Sensor and Steel Wire Integration

The destination of the designed sensor is to be integrated on the distal tip of movable core guidewires to measure the normal and shear forces.AnFEM modeling was done for the integration of the sensor and a steel wire. In this simulation, the steel wire passes through the ring and they are firmly integrated together by adhesive epoxy as shown in Fig. . The material properties are listed in table 1. The steel wire acts as force transmitting element when shear load applies. The stress field for normal and shear loadis presentedin Fig. .During normal loading the lateral stresscomponents in the four SiNWs are equal in magnitude with same direction as in Fig. 7 (a). When a transverse loading applied in the x- or y-direction, the two SiNWs along with the loading direction experience stress of the same magnitudebut opposite signs. The other two SiNWsperpendicular to the loading undergo torsion as in Fig. 7 (b). A linear relationship was observed between the applied force on the steel wire and the induced stress on the SiNW as shown in Fig. 8.

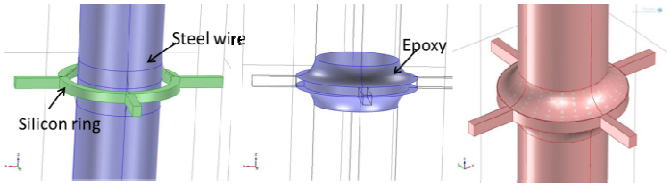
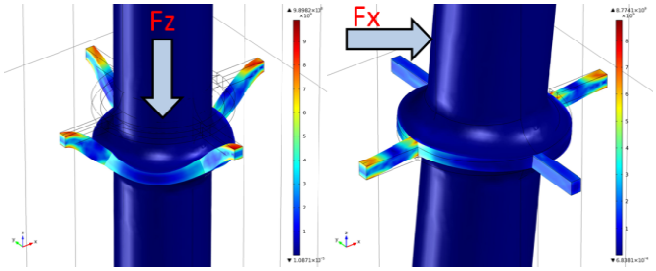


Fig. 6 Illustration of the steel wire integration with the ring sensor



(a) (b)

Fig. 7Von Mises stress filed of the steel wire integration on the ring sensor under normal (a) and shearload (b).

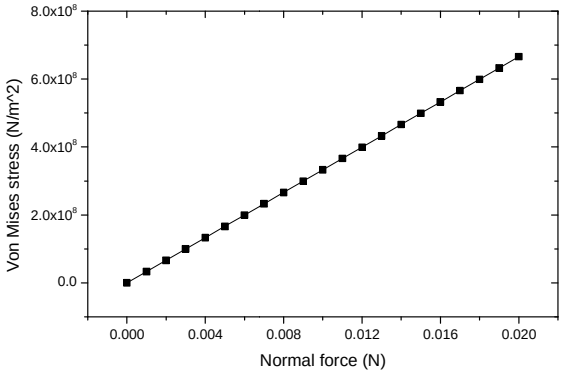


Fig. 8 Linear relationship between stress at the location of SiNW and the applied normal force on the steel wire

IV. CONCLUSION

A ring-shaped triaxial force sensor wasdesigned and simulated according to the mechanical structure of the guidewire with the purpose of mounting at the distal tip of the movable core guidewires. The integration scheme of the sensor and guidewire has been presented that have a new designed guidewire tip structure comprising two coils at the distal end. The designed sensor comprises a ring-shaped structure located at the center of four cantilever beams. PiezoresistiveSiNWs were used for sensing material to transform force to electric resistance. The sensor was designed and simulated usingCOMSOL,acommercial multiphysics simulation software, before the fabrication for stress analysis. Maximum stress location was found by FEM modeling. Mechanical behavior of the integration of the ring sensor and a steel guidewire was modeled and a linear relationship between applied load and the induced stress on the SiNWs was observed.

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