Proceedings of the ASME 2011 Dynamic Systems and Control Conference
DSCC2011
October 31 - November 2, 2011, Arlington, VA, USA

DSCC2011-6027

DESIGN & DEVELOPMENT OF A 2-DOF MINIATURE FORCE SENSOR FOR SURGICAL PROCEDURES

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ABSTRACT

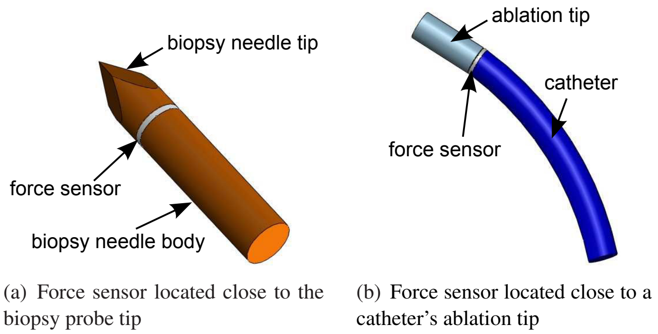
Force sensing is an important component for a number of surgical procedures as it can help to prevent undesirable damage to the tissue and at the same time provides the surgeons with a better "feel" of the tool-tissue interaction. However, most of the current commercially available multi-DOF force sensors are relatively large in size and it is a challenge to incorporate them into the surgical tool. Hence, a multi-DOF miniature force sensor is desired and this paper presents the design and development of a miniature 2-DOF force sensor. In order to achieve a miniature force sensor, microfabrication technique is used and the proposed force sensor is a capacitive-based sensor. The proposed force sensor can be used in a number of percutaneous procedures as well as catheter-based procedures. This paper presents the design and microfabrication process of the proposed miniature force sensor.

1 INTRODUCTION

Interaction force between the surgical tools and the tissues is an important information in a number of surgical procedures like breast biopsy [1] and cardiac catheterization. This information can be used to prevent undesirable damage to the tissues and also provide the surgeons with a better "feel" of the tissue. However, most of the commercially available multi-DOF force sensors are not sufficiently compact and is a challenge to incorporate them into the surgical tool. Hence, there is need for a multi-DOF miniature force sensor.

Researchers have proposed a couple of possible miniature force sensing solution. P. D. Goodyer *et al*. [2] propose an optical fiber pressure transducer for use in the upper airways by measuring the change in the reflected light intensity and P. Polygerinos *et al*. [3,4] propose using similar optical method for catheters. In order to miniaturize these fiber-optic sensors, equipments such as fiber-optic couplers and optical fibers are required, which inevitably increases the cost. Fiber bragg grating (FBG) sensors have been used in a number of other applications [5, 6] and is also a possible solution. However, like the reflected light intensity method, the disadvantage of the FBG method is the need for costly equipment. In addition, the mounting of the FBG sensors is challenging. H. Gao *et al*. [7] on the other hand proposed using PVDF. However, the length of the sensing element in that prototype is large and will hinder surgical procedures.

In order to achieve low cost with minimal required assembly, MEMS technique is explored in this paper. Manufacturing a piezoresistive based force sensor for multi-DOF sensing is a challenging task due to the challenges to form side wall piezoresistors and is hence not chosen. H.-L. Chau and K. D. Wise [8] proposed a miniature 1-DOF solid-state capacitive pressure sensor. This force sensor only has 1 DOF of sensing and the microfabrication process is not straightforward. Hence, the design of a two-DOF capacitive miniature force sensor is proposed in this paper. The targeted application includes percutaneous procedures such as breast biopsy and catheter-based procedures. In percutaneous procedures, the force sensor located closer to the tip of the biopsy probe can help to determine the needle insertion force and in catheter-based procedures, for example, the force sensor can help to determine the interaction forces between the catheter and inner wall of the blood vessel.



(a) Force sensor located close to the biopsy probe tip (b) Force sensor located close to a catheter's ablation tip

Figure 1. Examples of miniature force sensor placement

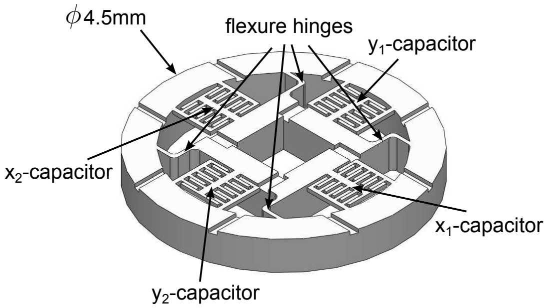


Figure 2. Sensor design

2 SENSOR DESIGN

Fig. 1 illustrates how the sensor is integrated into a biopsy probe or a catheter's ablation tip and Fig. 2 shows the capacitive force sensor design. The capacitor combs seen in Fig. 2 are the sensing elements and it can be seen that the capacitor combs on the device layer are separated by slots and structurally connected through the oxide and handle layer. The purpose of the oxide layer is to act as the insulator between the capacitor combs.

The flexure hinges provide the required spring effect in a force sensor and unlike most designs, the flexure hinges in the proposed sensor include the handle layer and are not limited to the device layer. This is to increase the robustness of the sensor without increasing the thickness of the device layer. Increasing the thickness of the device layer to improve robustness is not recommended as it will affect the fabrication of the capacitive combs. The effect of the moment on the flexure hinges due to forces exerted at the tip is not significant because the depth of the force sensor is significantly larger than the width of the flexure springs. In addition, the distance from the sensor to the tip is not large. The authors are also intending to calibrate the sensor with the tool at the system level, which will include the effect due to the moment to give a more accurate result.

The electrical contacts for the force sensor are located along the circumference of the device layer. Wires for the force sensor and instruments like an ablation device can be run through the space at the center. The present diameter of the force sensor is 4.5 mm and the size is expected to reduce after a few iterations. Finite element analysis of the force sensor has also been performed and the flexure hinges are designed such that the sensor can handle 1 N force in each principal direction. The dimensions of the flexure hinges can be changed according to the specific application.

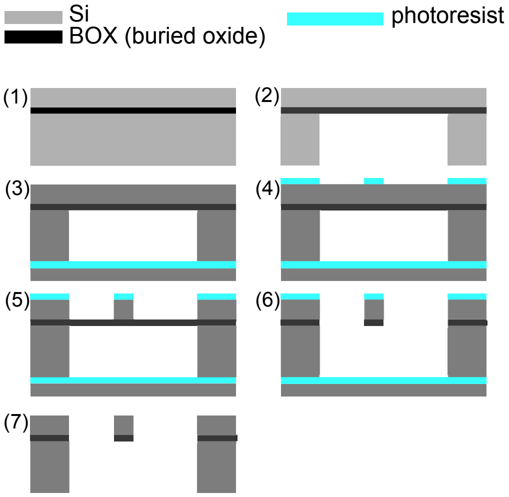


Figure 3. Microfabrication process

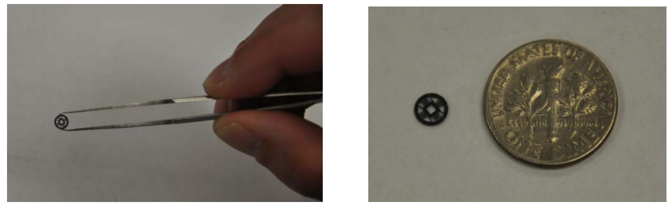
3 MICROFABRICATION

The underlying microfabrication technique of the proposed force sensor is based on the research group of B. J. Nelson [9–11] for cell manipulation applications. The underlying microfabrication technique is similar, but the design is different due to different targeted application. This microfabrication process is simple and results in a low cost force sensor with minimal assembly required.

The proposed capacitive force sensor was fabricated using the microfabrication facilities in the FabLab at the University of Maryland and the process is illustrated in Fig. 3 and described below:

1. Start with a double polished SOI wafer (65 μm highly doped Si, 1 μm SiO2 and 300 μm Si)
2. DRIE on the backside (handle) to form the flexure springs and the main body of the sensor
3. Bond the SOI wafer with a dummy wafer
4. Spin a layer of photoresist on the top side (device) and pattern the top side features
5. DRIE the top side (device) to form the capacitive comb, flexure springs and sensor body
6. RIE to remove oxide layer and the sensor will be structurally separated from the main wafer
7. Remove individual sensor from the dummy wafer by removing the photoresist

In order to etch high aspect ratio channels in silicon, AZ-4620 photoresist is used. The DRIE is performed using a Surface Technology Systems Etcher and the RIE is performed on Trion. The two-DOF capacitive force sensor is fabricated as a



(a) Miniature capacitive-based force sensor held by tweezers

(b) Force sensor in comparison with a US Dime

Figure 4. Prototype of the 2-DOF miniature force sensor

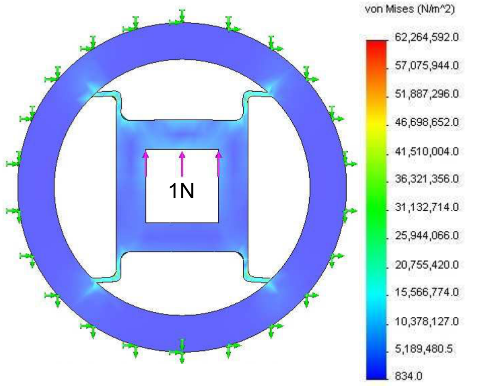


Figure 5. Finite element analysis of the force sensor

single piece and no assembly is required within the sensor. In addition, unlike other complicated fabrication processes, the proposed process requires only two masks. Another major advantage of the microfabrication process is that no cutting is required. The dice-free process to realize the force sensors (see step 7 of the microfabrication process) helps to prevent the fragile flexure structures from getting damaged.

4 PROTOTYPE

The force sensor is fabricated and Fig. 4(a) shows a photo of the force sensor held with a pair of tweezers while Fig. 4(b) illustrates the size of the force sensor in comparison with a US Dime. The diameter of this first prototype is 4.5mm and the height is 366μm. Finite element analysis has also been performed on the sensor design. Fig. 5 shows the deformation result when the sensor is subjected to a 1N force. For illustration purpose, the deformation scale for Fig. 5 is set to be 50 to better illustrate the deformation and the capacitive combs are removed in the figure because the plates cannot be clearly identified in the figure at this scale.

5 CONCLUSION

This paper presents a 2-DOF miniature force sensor for surgical procedures. The design, together with the microfabrication technique, are presented. The distinct advantages of the proposed 2-DOF force sensor is its 1) compact size, and 2) simple microfabrication process. In our future work, we plan to incorporate a third degree-of-freedom in force measurement as well as develop the necessary electronics to be able to measure the tissue and sensor interaction forces.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of NIH grant R01EB008713 as well as the 2011 UMCP-UMB seed grant program for part of this work. The authors would also like to acknowledge the support of the Maryland NanoCenter and its FabLab.

REFERENCES

[1] Tan, U.-X., Yang, B., Gullapalli, R., and Desai, J., 2011. “Triaxial MRI-Compatible Fiber-optic Force Sensor”. *Robotics, IEEE Transactions on,* **27**(1), pp. 65 –74.

[2] Goodyer, P., Fothergill, J., Jones, N., and Hanning, C., 1996. “The design of an optical fiber pressure transducer for use in the upper airways”. *Biomedical Engineering, IEEE Transactions on,* **43**(6), pp. 600 –606.

[3] Polygerinos, P., Puangmali, P., Schaeffter, T., Razavi, R., Seneviratne, L., and Althoefer, K., 2010. “Novel miniature MRI-compatible fiber-optic force sensor for cardiac catheterization procedures”. In Robotics and Automation (ICRA), 2010 IEEE International Conference on, pp. 2598 –2603.

[4] Polygerinos, P., Schaeffter, T., Seneviratne, L., and Althoefer, K., 2009. “Measuring tip and side forces of a novel catheter prototype: A feasibility study”. In Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on, pp. 966 –971.

[5] Park, Y.-L., Ryu, S. C., Black, R., Chau, K., Moslehi, B., and Cutkosky, M., 2009. “Exoskeletal Force-Sensing End-Effectors With Embedded Optical Fiber-Bragg-Grating Sensors”. *Robotics, IEEE Transactions on,* **25**(6), pp. 1319 –1331.

[6] Sun, Z., Balicki, M., Kang, J., Handa, J., Taylor, R., and Iordachita, I., 2009. “Development and preliminary data of novel integrated optical micro-force sensing tools for retinal microsurgery”. In Robotics and Automation, 2009. ICRA ’09. IEEE International Conference on, pp. 1897 –1902.

[7] Gao, H., Hao, Y., Du, J., and Wang, H., 2010. “Research on catheter sidewall tactile sensors”. In Information and Automation (ICIA), 2010 IEEE International Conference on, pp. 2238 –2241.

[8] Chau, H.-L., and Wise, K., 1988. “An ultraminiature solid-state pressure sensor for a cardiovascular catheter”. *Electron Devices, IEEE Transactions on,* **35**(12), Dec., pp. 2355 –2362.

[9] Muntwyler, S., Beyeler, F., and Nelson, B., 2010. “Three-axis micro-force sensor with tunable force range and sub-micronewton measurement uncertainty”. In Robotics and Automation (ICRA), 2010 IEEE International Conference on, pp. 3165 –3170.

[10] Beyeler, F., Muntwyler, S., and Nelson, B., 2009. “A Six-Axis MEMS Force-Torque Sensor With Micro-Newton and Nano-Newtonmeter Resolution”. *Microelectromechanical Systems, Journal of,* **18**(2), pp. 433 –441.

[11] Beyeler, F., Muntwyler, S., and Nelson, B., 2002. “A bulk microfabricated multi-axis capacitive cellular force sensor using transverse comb drives”. *Journal of Micromechanics and Microengineering,* **12**(6), pp. 832 –840.