Design and Analysis of MEMS Piezoresistive SiO_2 Cantilever-based Sensor with Stress Concentration Region for Biosensing Applications

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Abstract **This paper uses finite element method to obtain the optimal performance of piezoresistive microcantilever sensor by optimizing the geometrical dimension of both cantilever and piezoresistor. A 250 µm x 100 µm x 1 µm SiO_2 cantilever integrated with 0.2 µm thick Si piezoresistor was used in this study. The sensor performance was measured on the basis of displacement sensitivity and surface stress sensitivity. The resulting maximum displacement value is about 0.7 nm for an applied load of 250 pN. A comparison between polySi and SiO_2 cantilever has been carried out which shows the latter gives higher displacement for the same applied load. The sensor sensitivity was investigated by varying cantilever thickness as well as piezoresistor thickness. Simulation results show that the cantilever sensitivity is maximum when both the cantilever and the piezoresistor thicknesses are at minimum. Simulations were also conducted on the effects of incorporating various stress concentration region (SCR) designs at the bottom of the cantilevers. Cantilevers with incorporated stress concentration regions shows improved sensitivity over the cantilever without SCR. The cantilever with a rectangular shaped SCR extended up to the edge of the cantilever width yields a maximum Mises stress of 0.73 kPa compares to the other designs. For the same design, the cantilever with minimum SCR thickness of 0.2 µm yields maximum stress which results in maximum sensitivity.**

I. INTRODUCTION

MICROCANTILEVER has been proven as an outstanding platform for extremely sensitive chemical and biological sensors [1]. MEMS cantilever-based sensor is becoming popular in recent years due to its high sensitivity, high selectivity, easy to fabricate, and can be easily integrated with on-chip electronic circuitry. A MEMS cantilever-based sensor integrated with piezoresistive read out is normally used to measure the surface stress change induced from biochemical reaction since it performs well in liquid environments. The piezoresistor experiences a change in strain due to the cantilever bending and responds with a change in resistance. Apart from that, the piezoresistive read out system offers many advantages such as it is convenient to calibrate, readily deployable into integrated electromechanical system and does not require external detection devices [2-5]. However, the read out system has a lower resolution than the optical-based system which limits its sensing capability as the magnitude of the forces or stresses involved in the system is very small. Therefore, one solution to overcome the low resolution of the read out system is by increasing the sensitivity of the cantilever beam.

Many previous researches reported attempts made to improve the cantilever sensitivity using piezoresistive microcantilevers comprise of either a polysilicon piezoresistor integrated with silicon / silicon-nitride cantilever [6-7] or a doped single-crystalline silicon piezoresistor on a silicon cantilever [8]. Investigations made to improve the sensor sensitivity by optimizing the geometrical dimension of the cantilevers and incorporating stress concentration regions were reported [9-10]. Cantilever sensitivity to noise was also studied as one of the attempts to improve the cantilever sensitivity [11]. All these researches provided thorough understanding and strong foundation on silicon-based piezoresistive microcantilevers.

Recently, few researches on cantilever sensitivity were reported using SiO_2-based

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microcantilever sensors as they exhibited much higher displacement sensitivity compared to the silicon-based ones [12-14]. The SiO_2 microcantilever provides relatively higher mechanical displacement as thermally grown SiO_2 film features a lower Young's Modulus at about 57-79 GPa than silicon at 130 GPa. The higher mechanical sensitivity leads to larger surface-stress-induced bending of the cantilever which results in higher sensor performance and sensitivity. In the research, finite element model was developed to analyze electrical and mechanical response of the piezoresistive microcantilever in optimizing the sensor sensitivity. However, no simulation work has been carried out on SiO_2-based piezoresistive microcantilever incorporated with stress concentration region (SCR) to improve the sensor performance and sensitivity.

This research uses finite element method to obtain the optimal performance of SiO_2-based piezoresistive microcantilever sensor by optimizing the geometrical dimension of both cantilever and piezoresistor. A dual-leg thin layer of Si [100] was integrated on rectangular SiO_2 cantilever as piezoresistive material. Coventorware, a commercial finite element analysis tool for MEMS was used to develop a finite element model of the SiO_2 cantilever.

II. THEORY

Using Stoney's equation [15], the microcantilever displacement can be derived as a function of the differential surface stress as:

$$\delta = \frac{3L^2(1-\upsilon)}{Et^2}(\sigma_1 - \sigma_2) \qquad (1)$$

where δ is the cantilever displacement, υ the Poison's ratio, E the Young's modulus, $(\sigma_1\text{-}\sigma_2)$ the differential surface stress, L and t are the length and thickness of the cantilever beam, respectively.

The stress in the beam is zero at the centerline and increases linearly with the distance away from the centerline. Thus, the highest sensitivity can be achieved with a piezoresistor placed at the surface of the cantilever beam near the base. At that point, the stress can be calculated to be:

$$\sigma_{\max} = \frac{6L}{Wt^2}F = \frac{3Et}{2L^2}\delta \qquad (2)$$

where F is the applied force and W is the width of the cantilever beam.

The resulting fractional resistance change is given by:

$$\frac{\Delta R}{R} = \pi_l\sigma_{\max} = \beta\frac{6L\pi_l}{Wt^2}F = \beta\frac{3Et\pi_l}{2L^2}\delta \qquad (3)$$

where π_l is the longitudinal piezoresistive coefficient of silicon at the operating temperature and at a given doping and β is a correction factor between 0 to 1. Substituting (1) in (3), the expression for fractional change in terms of surface stress is obtained as:

$$\frac{\Delta R}{R} = \beta\frac{3\pi_l(1-\upsilon)}{t}(\sigma_1 - \sigma_2) \qquad (4)$$

Making the cantilever thickness as minimum as possible is the principal means to obtain the largest resistance change, thus the largest sensor sensitivity. Hence, introducing stress concentration region (SCR) on the cantilever by removing segments from under the base of the cantilever, in other words; thinning the cantilever will results in higher sensor sensitivity.

III. SIMULATIONS

The simulations are conducted using a mechanical domain solver, MEMMECH and a piezoresistor domain solver, MEMPZR from Coventorware. The dimension of a SiO_2-based piezoresistive microcantilever is shown in Fig. 1. The properties of materials used in this work are displayed in Table 1.

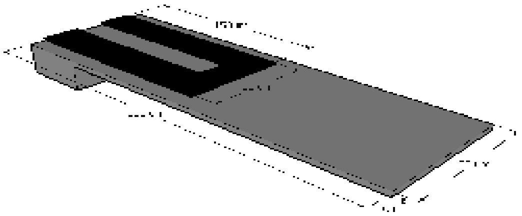

Fig. 1. The dimension of a rectangular SiO_2 cantilever integrated with a dual-leg Si piezoresistor.

Appropriate meshing is conducted on the solid model using a Manhattan parabolic type mesh structure. Unnecessary part of the cantilever structure which is the anchor is not meshed so as to reduce the computational load. Interactive forces commonly found in biochemical detection applications are in the range of ten to hundreds of pN [16]. As such, a 250 pN load is applied on the surface of the piezoresistive cantilever, taking the lower end value of the range.

Table 1 : Material Properties [13]

Parameters	Materials	
	Si	SiO_2
Young's Modulus (MPa)	1.30191×10^5	7.0×10^4
Poisson's Ratio	0.278	0.17
Piezoresistive Coefficients (MPa^{-1})	Π_{11} : 6.60×10^{-5} Π_{12} : -1.10×10^{-5} Π_{44} : 1.381×10^{-3}	-

IV. RESULTS AND DISCUSSION

From MEMMECH, the cantilever mechanical behavior in terms of displacement sensitivity as shown in Fig. 2 to Fig. 4 are obtained by fixing related boundary conditions and applying force on the surface of the cantilever.

Fig. 2 shows a comparison between PolySi and SiO_2 cantilevers of the same dimension on displacement sensitivity. It is clearly shown that SiO_2 provides higher displacement over PolySi for the same applied load making SiO_2 more suitable to be used as a highly sensitive cantilever sensor. As such, SiO_2 cantilever is used throughout the simulation process where higher displacement and surface stress sensitivity are expected.

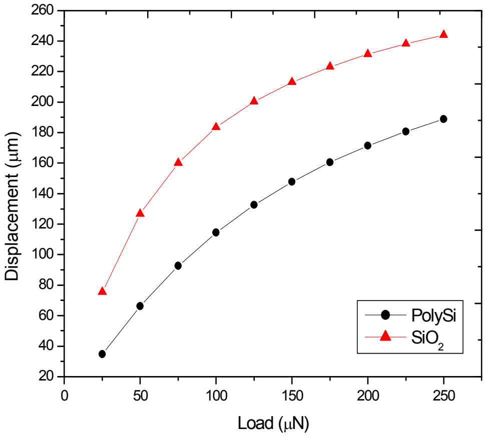

Fig. 2. A displacement comparison between PolySi and SiO_2 cantilever for the same applied load.

Using parametric study in Coventorware, it can be seen that both cantilever displacement and maximum Mises Stress showed the same trend where both values increased for increasing cantilever and piezoresistor thickness as shown in Fig. 3 and Fig. 4.

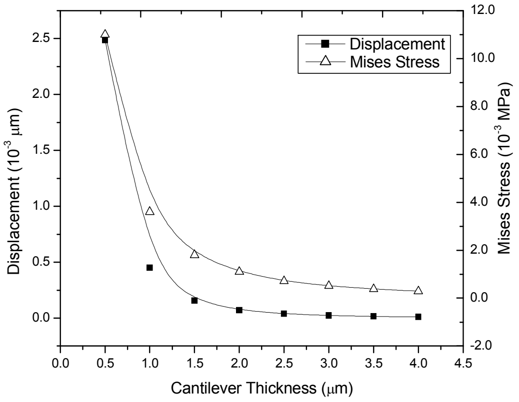

Fig. 3. Displacement and Mises Stress values as functions of cantilever thickness. Piezoresistor thickness is fixed at 0.2 μm.

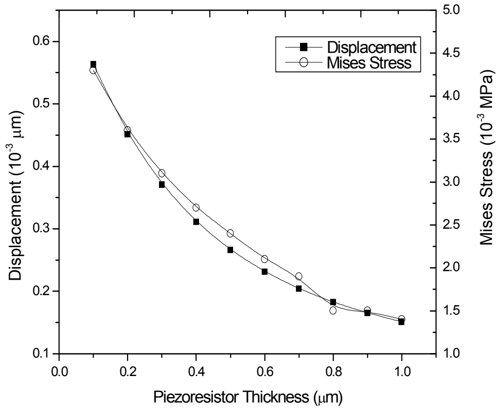

Fig. 4. Displacement and Mises Stress values as functions of piezoresistor thickness. Cantilever thickness is fixed at 1.0 μm.

Results from MEMMECH are then used in MEMPZR to compute piezoresistive behavior such as resistance and current changes resulted from applied load in MEMMECH. Cantilever surface stress sensitivity is obtained by measuring the change in resistivity when a 250 pN load is applied on the cantilever with respect to no load condition. Note that 1 V potential is applied on piezoresistor to generate current flow in piezoresistor. As can be seen in Fig. 5, maximum cantilever sensitivity is obtained when both cantilever and piezoresistor thickness are at minimum.

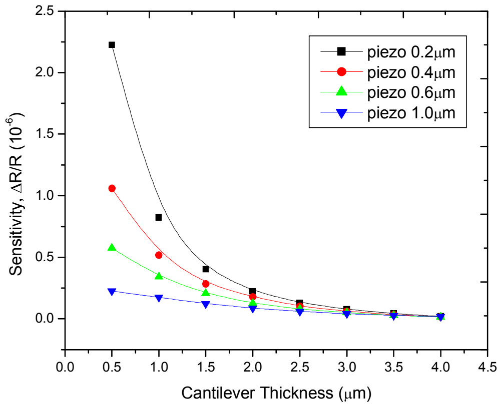

Fig. 5. Sensitivity, ΔR/R as a function of cantilever thickness at different piezoresistor thickness

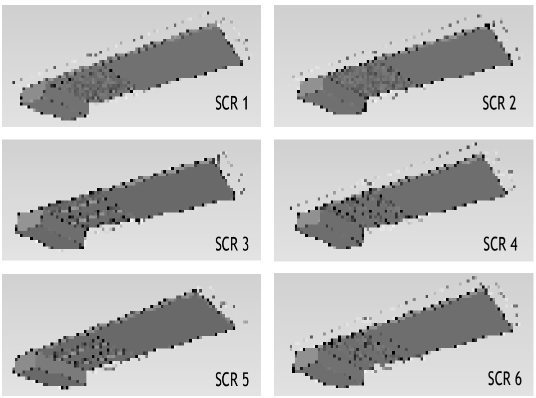

Fig. 6. Six SCR designs are considered. Cantilever thickness is 1.0 μm, piezoresistor thickness is 0.2 μm.

The effect of incorporating SCR to improve cantilever sensitivity is studied by removing segments at the bottom of the SiO_2 cantilevers for six designs as shown in Fig. 6. The 0.2 μm deep segments are removed along the piezoresistor area so as to reduce thickness only at that particular area.

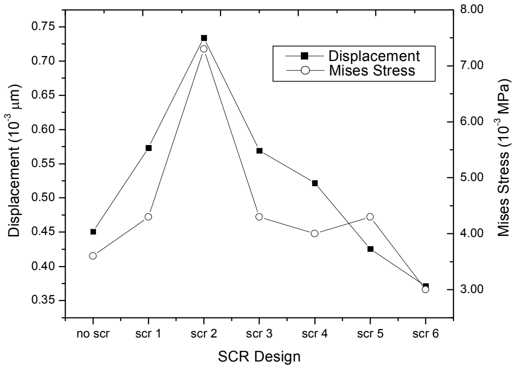

Fig. 7. Displacement and Mises Stress values as functions of SCR designs.
Cantilever thickness is fixed at 1.0 μm, piezoresistor thickness is 0.2 μm.

From Fig. 7, it is shown clearly that cantilever incorporated with SCR Design 2 yields maximum displacement and Mises Stress compare to other designs. As shown in Fig. 8, the sensitivity, ΔR/R shows much improvement for the said design over the rest of the designs.

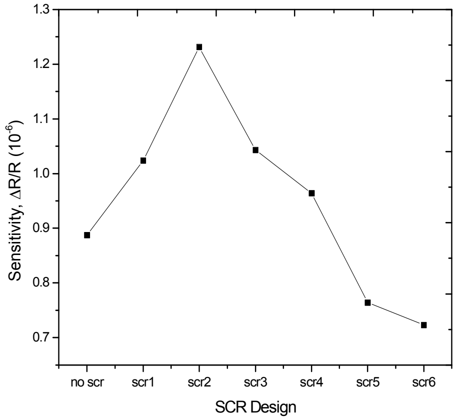

Fig. 8. Graph of sensitivity, ΔR/R over SCR designs. Cantilever thickness is fixed at 1.0 μm, piezoresistor thickness is 0.2 μm.

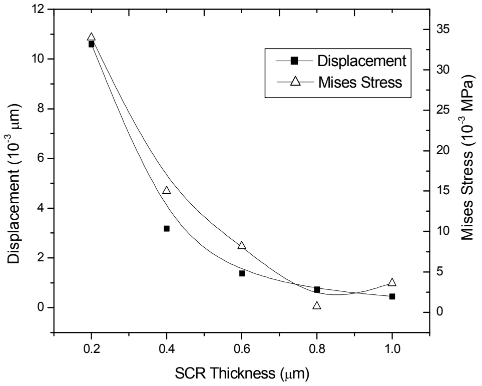

Fig. 9. Displacement and Mises Stress values as functions of SCR thickness for cantilever incorporated with SCR Design 2.

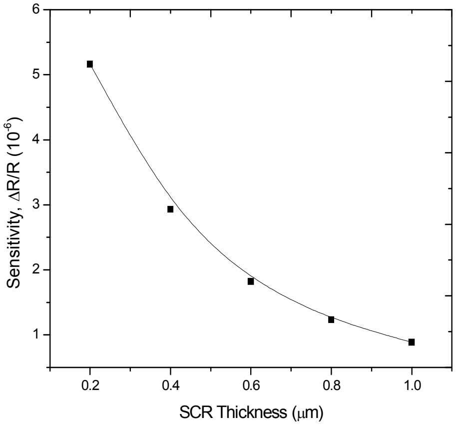

Fig. 10. Graph of sensitivity, ΔR/R over SCR thickness for cantilever incorporated with SCR Design 2.

Further simulation is conducted on a cantilever incorporating SCR Design 2 to study the effect of SCR thickness on the cantilever sensitivity. The SCR thickness is the thickness measured from the top surface of the cantilever to the edge of the removed segment. For the said design, both maximum displacement and surface stress sensitivity are observed for SCR thickness at 0.2 μm as clearly shown in Fig. 9 and Fig. 10.

V. CONCLUSION

In this paper, geometrical dimensions of both cantilever and piezoresistor are analyzed using finite element analysis technique to obtain optimal performance of piezoresistive microcantilever sensor. Minimum cantilever and piezoresistor thicknesses yield the highest displacement and surface stress sensitivity. However, the optimum structure thickness also depends on fabrication constraint and capability. From the six SCR designs, rectangular shaped SCR Design 2 which extended up to the edge of the cantilever width shows the highest sensitivity compare to the other designs.

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