Excerpt from the Proceedings of the 2011 COMSOL Conference in Boston

Optimization of Design Parameters of a Novel MEMS Strain Sensor Used for Structural Health Monitoring of Highway Bridges

H. Saboonchi*[1] and D. Ozevin[1]
[1] Civil Engineering Department, University of Illinois at Chicago
*842 W Taylor St. ERF 3073 Chicago, IL 60607, hsaboo2@uic.edu

Abstract: The novel Micro Electro Mechanical System (MEMS) based Piezoresistive stain sensor is presented in this paper. The main goal of this sensor is to monitor the localized strain in the highway bridges especially near the crack tips. Monitoring the crack growth on the bridges can lead to early detection and prevention of bridge failures.

The main disadvantage of conventional stain gauges in terms of study of cracks is that the strain gradient highly influences the measurement and the average strain will be measured over their surface areas. In order to overcome this problem, the MEMS strain sensor developed in this study, is made up of single crystal silicon and its area is 100 µm x 400 µm which prevents the strain gradient effect at the vicinity of crack tip. The sensor has a novel U shape configuration with the open side of U shape faces the crack tip. This feature and geometrical features add more amplification to the strain.

COMSOL Multiphysics has been used to simulate the device and optimize the geometric design parameters.

Keywords: MEMS Strain Sensor, Crack tip, Structural Health Monitoring, Highway Bridges

1. Introduction

In aging civil structures, especially highway bridges, cracks eventually form due to fatigue loading and increasing demand in transportation networks. The bridges are routinely inspected, mostly visual; however, there are possibilities of catastrophic failures due to excessive loading or design errors. Structural health monitoring (SHM) of highway bridges contains continuous monitoring of the structures using a set of sensor networks for critical cracks and other forms of damage such as corrosion. The determination of the stability of existing cracks could prevent catastrophic failures.

Strain gauges are nonintrusive, effective sensors in order to monitor live load strains in highway bridges, and have been continuously used in various structures for SHM. The measurement of a series of strain-time traces as the crack propagates allows an accurate determination of the crack velocity, the propagation toughness K_{1d}, and the crack arrest toughness K_{1a} (Dally and Berger 1993[1]).

The drawback of conventional strain gauges is minimum size limitation with sufficient sensitivity, which significantly affects the accuracy of the strain reading in the zones of high strain gradient such as crack tips. They cannot measure strain better than the average of strain over their areas. The measurement error significantly increases when the foil type strain gauges are placed closer to the crack tip (Dally and Berger 1993[1]). The sensitivity of strain gauge systems can be improved further if the sensor area is reduced, and the sensor has high dynamic range in order to detect large strains as in the cases of crack tips. Such improvements can be achieved by the development of piezoresistive MEMS strain gauges as discussed in this paper.

2. Material for MEMS Strain Sensor

One of the key parameters to describe the sensitivity of strain gauges is called the Gauge Factor (GF). The Gage Factor of a strain sensor is defined as the normalized change of resistivity $\Delta R/R$ over strain:

$$GF = \frac{\Delta R/R}{\varepsilon} \quad (1)$$

The change in resistance is calculated from equation 2.

$$\Delta R/R = \varepsilon * (1 + 2 * \nu) + \Delta\rho/\rho \quad (2)$$

where ν in this equation is Poisson‟s ratio; $\Delta\rho/\rho$ is the normalized change in resistivity. The fractional change in resistivity can be approximated in a linear proportion to stress as follows (Nathan and Baltes 1999[2]):

$$\frac{\Delta\rho_{ij}}{\rho} = \sum_{k,l} \pi_{ijkl}\sigma_{kl} \text{ with } i, j, k, l = 1,2,3 \quad (3)$$

where □ is piezoresistivity coefficient, *T* is stress.

Since Smith (1954)[3] demonstrated the piezoresistance properties of germanium and silicon, doped silicon (n type or p type) has been used extensively in the sensor design, especially pressure sensors. The piezoresistivity coefficient varies for different material, n-doped or p-doped, doping level and also direction of sensing element and its plane (Kanda 1982[4]). For metals the normalized change in resistivity is very small; however it could be even 100 times bigger than the first term for silicon.

By substituting equation 2 into equation 1 and replacing stress from σ = E * ε and $\Delta\rho/\rho$ from equation 3, GF is calculated from equation 4:

$$GF = 1 + 2 * \nu + \pi_1 * E \qquad (4)$$

where E is Young"s modulus and equals 170 GPa for silicon. The piezoresistivity coefficient of n-doped silicon in longitudinal direction and (100) orientation is -102.2E-11 Pa^{-1} (Smith 1954[3]).

In this study, the sensing element of the MEMS strain sensor is made of n-doped silicon which can have gage factor up to 135 as oppose to 2 for the conventional metal strain gauges.

3. Geometry Design

In reality since the strain and stress should be transferred through a substrate layer and an adhesive layer, they may not be the same in the sensing element. It has been shown that this reduction could be about half of the original values (Hautamaki et al. 2003[5]). In order to overcome this effect, two approaches have been implemented: (1) reducing the thickness of the substrate layer by forming a thin diaphragm, and (2) using the geometric features of the sensor design as a second amplification of stresses in the sensing element. Cao et al. (2000)[6] and Kim et al. (2010)[7] have used a thin diaphragm in their studies to compensate the geometry effect. Mohammed et al. (2011)[8] have used geometrical features as an amplifier. In this paper, both of these methods have been applied in the design of novel MEMS sensor using the COMSOL simulations for the geometry optimization. Creating a „U shape" substrate reduces the stiffness effect of the substrate to transfer strain from the structural surface to the sensing area. The sensor design also reduces the effect of sensor installation on the stress field around the crack tips.

Figure 1 shows the materials used to form „U shape" and dimensions. The dimensions of the sensing element are 5 □m thickness, 400 □m length and 100 □m width. As shown in the next section, based on the numerical simulations, the sensing element size significantly reduces the strain gradient effect at the near crack field while the gage factor is relatively high as compared to conventional foil gauges.

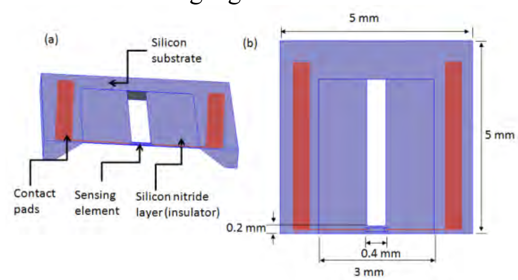

Figure 1. The geometric configuration of the MEMS strain sensor; (a) perspective view with the materials, (b) planar view with the dimensions.

4. Analysis Methods

In order to validate the ability of capturing the strain at the crack tip without being influenced by the strain gradient, a model of compact tension (CT) specimen (ASTM E399-09[9]) made of structural steel was developed using COMSOL. The strain sensor was mounted on the notch tip (near field zone of the stress concentration area) at one side of the specimen. Figure 2 illustrates the CT specimen deformation as well as the sensor location.

The material properties of silicon and structural steel available in the program are used. It is important to note that the yield stress and the elasticity modulus of silicon are 7 GPa and 170 MPa while the yield stress and the elasticity modulus of steel are 0.25 GPa and 250 MPa. The comparison of two materials indicates that silicon can resist large deformation occurring in the structural steel without reaching to the yield point.

Finite element method implemented in the COMSOL Multiphysics software has been used to calculate the structural deformation and the stress and strain field on both specimen and the sensor. Based on these calculations, new value for resistivity including the change due to stress has been calculated. For these purposes, the

COMSOL study included a parametric sweep of the applied load to the CT specimen as 0, 1, 5, 10, 20 and 50 kN. The solid mechanics and the electric current models were coupled in order to obtain the resistance change of the sensing element under given loading. The electrical conductivity of the silicon is modified in order to consider the conductivity change with the stress due to the piezoresistivity property of silicon: □=1e2[S/m]/(1+102e-11[Pa^-1]*solid.sx[Pa]). The value 102e-11 is the piezoresistivity coefficient of silicon in the longitudinal direction.

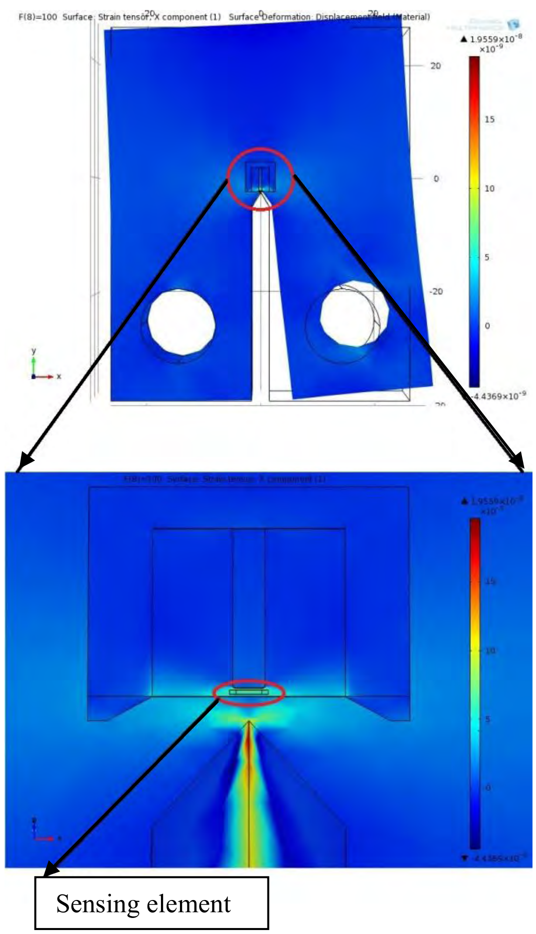

Figure 2. Single MEMS strain sensor coupled with steel compact tension specimen. The image shows the surface plot of horizontal strain matrix.

5. Results

The effect of sensor installation was investigated by comparing the strain contours of front and back sides of the CT specimen which shows that the sensor presence at the near field of the notch has minor effect in strain distribution, as shown in Figure 3 (back side) and Figure 4 (front side). These plots also demonstrate another advantage of the clip-shape substrate designed in this study as that the presence of sensor does not affect the strain gradient at the close vicinity of notch tip.

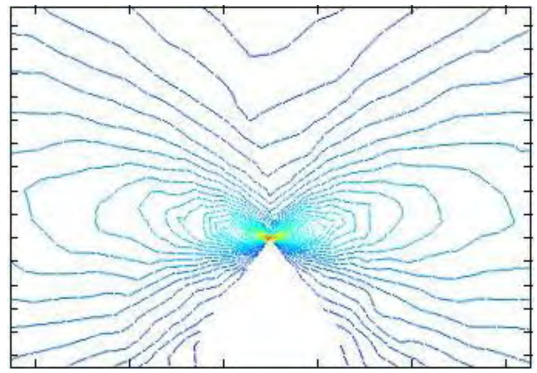

Figure 3. Strain contour of back side of specimen which is not affected by sensor installation

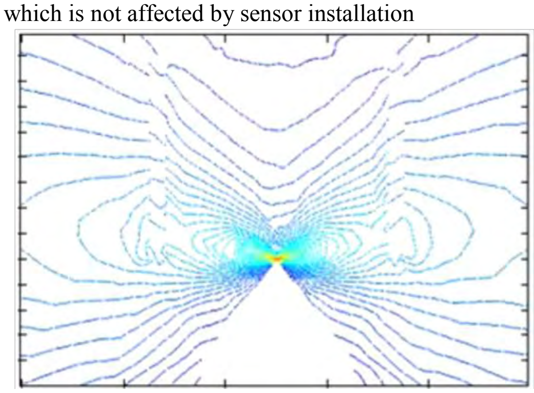

Figure 4. Strain contour of front side of specimen which shows the effect of sensor installation on crack tip

The parametric studies in order to demonstrate the linearity of sensor response (output) to varying load or strain values (input) was illustrated in Figure 5. The figure shows the strain values at the notch tip (blue and green) and at the sensing element (red). The data in the figure for the MEMS strain sensor represents the average strain over the area of the sensing element as shown in Figure 2. The difference in the strain values on the steel surface and the sensing element under given loading is because of the geometric features of the MEMS strain sensor. In other words, the sensor is not in the direct contact with the surface, and the thin diaphragm and „U shape‟ design amplify the strain that the MEMS strain sensor is exposed to. The geometry of the MEMS strain sensor can be designed such a way that the strain on the steel surface and the strain on the sensing element will be identical.

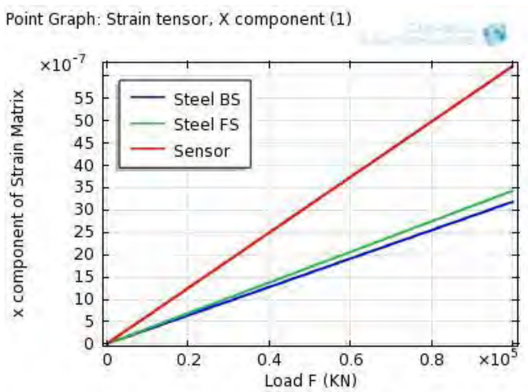

Figure 5. Strain VS in both sensor and related point in the steel (front and back side)

As mentioned earlier, the electrical conductivity of the silicon is modified in order to consider the conductivity change with the stress due to the piezoresistivity property of silicon. Using the electrical current mode (one electrical pad connected to the sensor as ground, the other one as terminal with 1 V excitation signal), the change in resistance due to loading of the structural steel is identified by R=V/I or voltage over current. The effects of stress on the resistance and resistance change of the MEMS strain sensor are shown in Table 1.

Table 1. Resistance and resistance change for different loadings.

F [KN]	R [Ω]	ΔR [Ω]
0	8054.979852	0
1	8055.047659	0.067806924
2	8055.115466	0.135613771
5	8055.318886	0.339034262
10	8055.65792	0.678068132
20	8056.335987	1.356134694
50	8058.370177	3.390325008

Based on the values in Table 1, actual gage factor of the MEMS strain sensor (GF_{act}) has been calculated to be 264 which is about 132 times higher than the gage factor of conventional metal strain gauges and about twice of theoretical gage factor of silicon (GF_{theo}) which is 135. The result illustrates the positive effect of the amplification of stresses by geometrical features in order to detect small strain values as well as small strain changes.

6. Discussions

The design parameter, which limits the minimum diaphragm length, is the total resistivity of the sensor (i.e. the higher the resistivity is, the higher the current loss is for transmitting the resistance change over long distances). As thin diaphragms result in higher gauge factors as shown in this study, the length of the sensing element should not be high in order to design the sensor with a reasonable resistance value. It is important to note that the thickness and width of the sensing element (i.e. area) are proportional to the resistance while the length of the sensing element is inversely proportional to the resistance. The optimized thickness of the diaphragm (including silicon and insulator layer silicon nitride) is calculated as 10µm having 5 µm thick silicon for the sensing element. The total resistivity of the MEMS strain sensor is about 8 kΩ with the geometric dimensions as 400 □m long, 100 □m wide and 5 □m thick.

7. Conclusions

The novel geometry of the MEMS strain sensor modeled using the COMSOL software shows significant improvement in the gage factor, in other words the sensitivity of strain sensor to strain changes. The geometry has a small footprint that provides the ability to capture strain values at the vicinity of crack or notch tips without influenced by the high gradient strain fields. The unique design of the sensor substrate does not affect the near field strain distribution of the notch tip due to the presence of sensor package.

8. References

1. Dally, J.W. and Berger, J.R. "The Role of the Electrical Resistance Strain Gauge in Fracture Research," Experimental Techniques in Fracture, Edited by J.S. Epstein, Wiley VCA Weinheins, pp. 1-39,(1993).

2. Nathan, A. and Baltes, H. Microtransducer CAD: Physical and Computational Aspects. Springer Wien New York (1999).

3. Smith, Charles S. "Piezpresistance Efect in Germanium and Silicon." *Physical Review* 94, no. 1, 42-49, (April 1954).
4. Kanda, Y., A Graphical Representation of the Piezoresistance Coefficients in Silicon, IEEE Transactions on Electron Devices, Vol. ED-29, No. 1, pp. 64-70, (January1982).
5. Charles Hautamaki, Li Cao, Jia Zhou, Susan C. Mantell, Calibration of MEMS Strain Sensors Fabricated on Silicon: Theory and Experiments, *JOURNAL OF MICROELECTROMECHANICAL SYSTEMS* 12, no. 5: 720-727 (OCT 2003).
6. Li Cao, Tae Song Kim, Susan C. Mantell, Dennis L. Polla, Simulation and fabrication of piezoresistive membrane type MEMS strain sensors, *Sensors and Actuators* 80: 273–279 (2000).
7. Yongdae Kim, Youngdeok Kim, Chulsub Lee, and Sejin Kwon, Thin Polysilicon Gauge for Strain Measurement of Structural Elements, *IEEE SENSORS JOURNAL* 10, no. 8, 1320-1327 (Aug 2010).
8. Ahmed A. S. Mohammed, Walied A. Moussa, and Edmond Lou, Development and Experimental Evaluation of a Novel Piezoresistive MEMS Strain Sensor, *IEEE SENSORS JOURNAL* 11, no. 10: 2220-2232 (Oct 2011).
9. Standards, ASTM International, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIC of Metalic Materials, In *Designation: E399-09*, ASTM International Standards (last edited on Dec 2010).