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ScienceDirect

Procedia Engineering 87 (2014) 1362 – 1365

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

High Sensitivity Micro-Machined Piezoresistive Strain Sensor

D. Caseiro[a], S. Santos[a], C. Ferreira[ab]*, C. Neves[ab]

[a]*ESTG, Instituto Politécnico de Leiria, Apartado 4163, 2411-901 Leiria, Portugal*
[b]*INESC Coimbra, Rua Antero de Quental 199, 3000-033 Coimbra, Portugal*

Abstract

This paper presents a micro-machined piezoresistive sensor capable of measuring very small strains. The sensor design, based on piezoresistive sensing technology, was optimized by the numerical method using Finite Element Method (FEM) to enhance sensibility. The high sensibility is achieved through a reduction of section and through the action of the bending moment. As a result, a sensor with a sensitivity of 569.4608 µV/V/µε, which can be fabricated by the SensoNor MultiMEMS process, is proposed. Furthermore, practical essays with macro prototypes confirmed and validated the numerical analysis. Such a sensor can be a direct replacement for the strain gauges and its very high sensitivity opens the door to many other applications, that otherwise would not be possible.

Peer-review under responsibility of the scientific committee of Eurosensors 2014

Keywords: MEMS; Strain Sensor; Piezoresistive

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1. Introduction

The metallic strain gauges were invented by Edward E. Simmons and Arthur C. Ruge in 1938 and until today are the standard devices for measuring mechanical strain. Their dominance is forged by the low cost, high linearity, ease of use, being an established technology and because they can be easily installed on various types of surfaces. Despite of all these advantages, metallic strain gauges present a reduced sensitivity, which somewhat limits their applications. Also, precise conditioning electronics are mandatory to obtain reliable values, making the measurement systems more complex and expensive [1].

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* Corresponding author. Tel.: (351) 244820300; fax: (351) 244820310.
E-mail address: ferreira@ipleiria.pt

Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.696

Micro-electro-mechanical sensors (MEMS) feature very high sensitivities, reliability and low price. Moreover, the fact that electronic signal conditioning can be added to the sensor silicon die makes MEMS the state of the art in the measurement technology [2-4]. Even if diverse force sensors have been presented in literature [5-7], none of them has the function of replacing the strain gauges. Therefore, we propose a micro-machined piezoresistive strain sensor (shown in Figure 1) optimized for high sensitivity.

2. Sensor design

With dimensions of 3×3×0.4 mm^3 the sensor was developed by numerical method to fulfill the rules and limitations of the former SensoNor Multi-Project wafer service MultiMEMS [8]. The sensor sensitivity resulted from the optimal conjunction of both the strain amplification performed by the mechanical design of the sensor and the strain to electrical output conversion.

Mechanical strain amplification designs from literature [9] were studied, most of them use levers to increase the strain sensitivity. Although, the best performance regarding the sensor sensitivity, was achieved with the design presented in Figure 1, where the mechanical stress concentration is achieved by the reduction of section in the sensor y and z axes (width and thickness, respectively) and through the action of a bending moment. The sensor thickness goes from 400 µm (wafer thickness) to 23.1 µm, intermediary thickness defined by the n-well areas to 3.1 µm used in the central area of the sensor (Figure 2(b)). Regarding to the y axis the area reduction is made through the etching (reactive ion etching (RIE)) of two trapezium shape areas at the sensor surface. The elevation of the sensor central ("sensing") area in relation to the sensor base, where deformation is applied, results in a bending moment which also plays an important role to the sensor sensitivity.

Concerning the electrical conversion, from the multiple possible arrangements for sensitive piezoresistors (note that the number of elements forges the dimension of the sensor central area), was used a full Wheatstone bridge circuit placed in the central area of the sensor, where the sensor design concentrates the mechanical stress. This configuration results in the highest overall sensibility of the sensor and eliminates the output sensitivity to the temperature due to the resistance variation of piezoresistors. The dimensions of central area of the sensor, with a thickness of 3.1 µm, were optimized to maximize the difference between longitudinal and transversal stress, while having enough room for the sensing elements. The numerical results for the mechanical stress distribution along a center line of the sensor upper surface can be seen in Figure 2(a), where in the central area of the sensor with 53 µm length, centered at1.8 mm, is evident the high peak of the mechanical stress.

Overall, the proposed sensor presents a sensitivity of 569.4608 µV/V/µε, while, for comparison, the sensitivity of a metallic strain gauge (with a gauge factor of 2.15) in a half Wheatstone bridge configuration is about 0.5375 µV/V/µε.

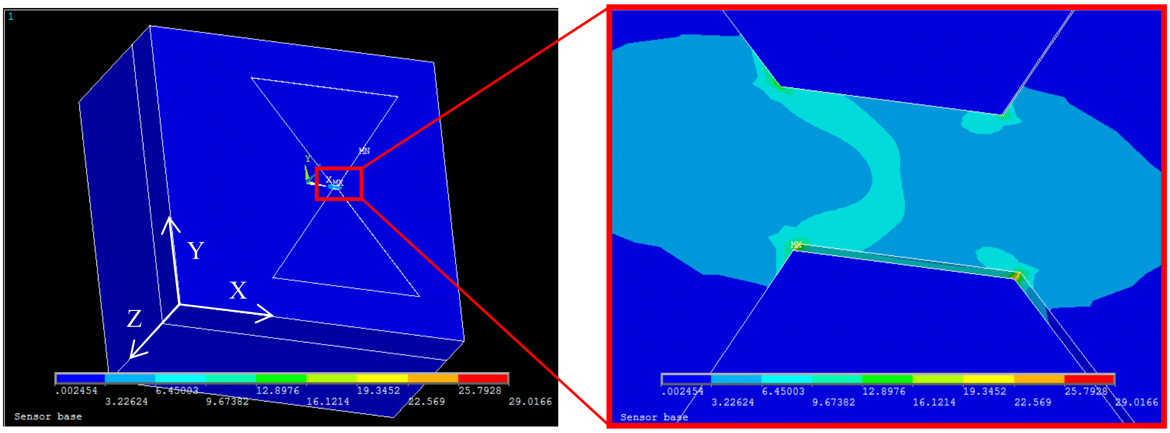

Fig. 1. Geometry of proposed micro-machined piezoresistive strain sensor, with focus to the equivalent stress on the sensor central area.

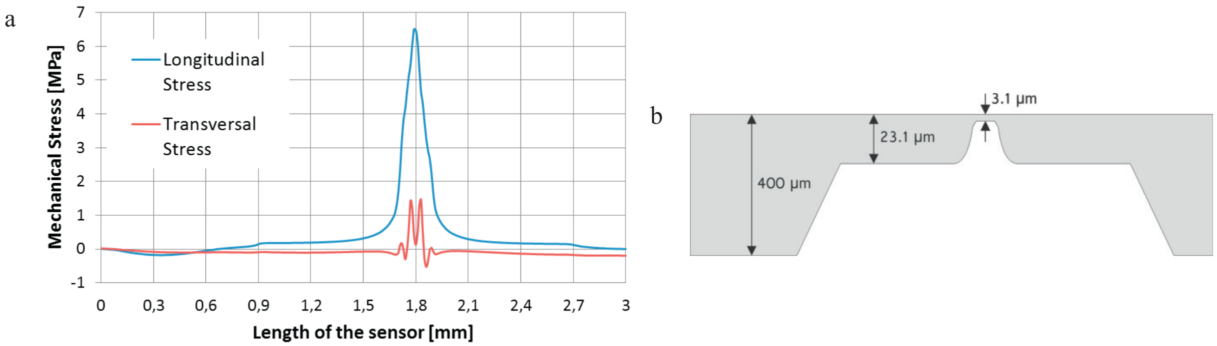

Fig. 2. (a) Numerical results for the longitudinal and transversal mechanical stress along the upper surface of the sensor. The results shown are for a line passing through the sensor center. The difference between the longitudinal and the transversal stress is an indicator of the sensor sensitivity to the mechanical strain; (b) Section view of the sensor across the central Y-Z plane (not scaled).

3. Experimental test and results

To validate the proposed concept, various macro prototypes of the mechanical sensor design were fabricated. One of the prototypes is shown in Figure 3(a), with a metallic strain gauge used as sensing element. The experimental tests, as shown in Figure 3(b), consisted on applying cycle of loads on a specimen instrumented with two strain sensors. The first sensor was a standard metallic strain gauge directly applied to the specimen surface. The fabricated macro sensors prototypes were used as the second sensor glued in the opposite side of the specimen. An identical metallic strain gauge was used as sensing element in the macro sensor prototype. This setup ensures that both sensors are subject to same mechanical condition, and therefore a comparison between both measurements indicates the amplification factor achieved in the strain sensitivity by the mechanical geometry of proposed design.

As shown in Figure 4 the strain measured by the strain gauge placed on the prototype is multiplied by a factor of 1.93 compared to the one measured by the gauge placed directly on the specimen. The practical results are in accordance with the numerical ones (2.21) for the same geometry, being the difference explained mainly by the dimensional inaccuracy of the fabricated prototype and the bonding quality of the macro prototype to the specimen surface. The results obtained with the macro sensors enabled us to validate the strain amplification function of the geometry and the numerical analysis performed. Therefore, the sensitivity of a strain sensor fabricated through micro-machining would be expected to get close to the numerical results presented.

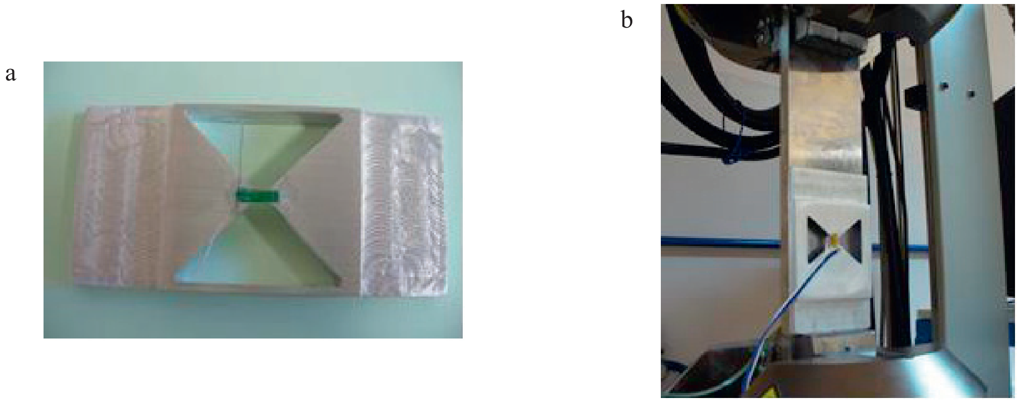

Fig. 3. (a) Macro prototype of the proposed concept, built for the experimental tests, where a metallic strain gauge was used as the sensing element; (b) Practical essays done on an Instron 8802J4310. A test specimen was instrumented with the prototype of proposed sensor on one side and with a strain gauge placed directly on the other.

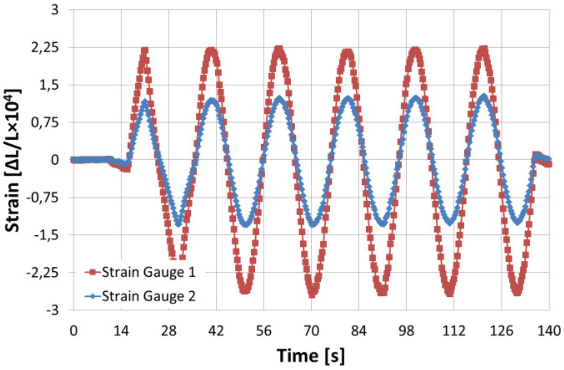

Fig. 4. Practical results for the strain measured on both identical strain gauges: Strain Gauge 1 – installed in the macro sensor and Strain Gauge 2 – installed directly on the test specimen.

4. Conclusions

This article presents a high sensitivity micro-machined piezoresistive strain sensor concept which aims to directly replace the traditional strain gauges. The concept was optimized by the numerical method, being tested several designs and then being optimized to achieved the maximum strain sensibility.

Experimental tests with macro prototypes similar to the proposed sensor allowed the validation of the results obtained by the numerical method and to verify the sensitivity amplification provided by the geometry design.

The manufacturing of the micro-machined piezoresistive sensor, by the SensoNor MultiMEMS Multi-Project wafer service, will result in a sensor with a strain sensitivity of 569.4608 μV/V/με, while, for comparison, the sensitivity of a metallic strain gauge in a half Wheatstone bridge configuration is about 0.5375 μV/V/με.

Such a high sensitivity strain sensor will make possible many applications, like for example: measure the strain in bridges, vehicle structures and suspension, indirect measuring of forces in robotics and medical industries to name a few, otherwise not possible/feasible with strain gauges. Moreover, the possibility to have very low temperature sensitivity and an amplified analog output will increase the precision of the measuring systems.

Acknowledgements

This work has been partially supported by the Portuguese Foundation for Science and Technology under project grant PEst-OE/ EEI/UI308/2014.

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