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Optimized design of a piezoresistive pressure sensor with measurement span of 1MPa

C. Ferreira [a, b, *], C. Grinde [c], R. Morais [d], A. Valente [d], C. Neves [a, b], M. Reis [d]

[a] Escola Superior de Tecnologia e Gestão, Instituto Politécnico de Leiria, Apartado 4163, 2411-901 Leiria, Portugal
[b] INESC Coimbra, Rua Antero de Quental 199, 3000-033 Coimbra, Portugal
[c] Faculty of Science and Engineering, Vestfold University College, Horten, Norway
[d] ECT-Departamento de Engenharias, UTAD/IEETA/CITAB, Quinta de Prados, 5000-911 Vila Real, Portugal

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Abstract

This paper presents a piezoresistive pressure sensor with a measurement span of 1MPa and capable to withstand peak pressures around 10MPa. The sensor design, based on a square membrane, was optimized for enhanced sensitivity, high linearity and low sensitivity variations between fabricated samples. Being the asymmetry of the mechanical stress peaks, the ratio between the membrane area and its thickness, and the tolerances of the bulk micromachining process considered for the optimal positioning of the piezoresistive sensing elements. Practical results show a mean sensitivity of 30.9mV/V/MPa with a standard deviation of 0.65mV/V/MPa and a linearity error of 0.15% of the scale span.

Keywords: MEMS; Piezoresistive; Pressure Sensor; Flat Membrane Design

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1. Introduction

To develop a silicon micro-machined piezoresistive pressure sensor with a measurement span of 1MPa and capable to withstand peak pressures of 10MPa, a membrane design with a small ratio between edge length and thickness is necessary. Such a membrane is commonly fabricated by the bulk micromachining of silicon wafers, being its dimensions forged by the wet etching process. Membrane designs with a central mass, bossed membrane, due to its smaller deflections and to the possibility to have sensing

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

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elements subjected to similar, absolute value and shape, but of opposite value mechanical stresses (sensitivities), results in designs with improved linearity. However, such designs are very difficult to realize (convex corners, deep etching distances and small distances between convex and concave corners) and are highly affected by the tolerances of the wet etch process, resulting in a device with low sensitivity and high sensitivity variations among fabricated samples. For the above presented reasons flat membrane designs are preferred. In flat membrane designs the main causes for nom linearity are; the nonlinear relation between applied pressure and mechanical stress (related to the membrane dimensions and displacement) and the sensitivity matching of the sensing piezoresistors in the Wheatstone bridge [1,2]. In low range pressure sensors, Fig. 1.(a), sensing elements are undoubtedly placed inside the membrane area, near to its edges, where the sensitivity is higher [2,3]. More reservations arise for designs in the medium and high pressure ranges, Fig. 1.(b), with a low ratio between membrane area and thickness, where the same practice is debatable. Commonly, sensing piezoresistors, especially the ones placed perpendicular to the nearest membrane edge, are also divided in multiples to improve their overall exposition to the mechanical stress (sensor sensitivity) [4]. Furthermore, the present work optimizes the position of the sensing piezoresistors considering the variations in the membrane dimensions, due to fabrication tolerances, for a compromise between sensitivity and sensitivity variations.

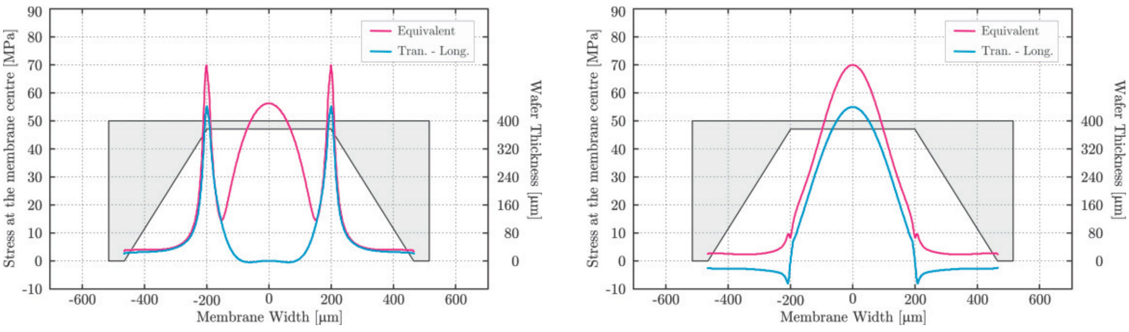
(a) (b)

Fig. 1. Characteristic equivalent stress on the surface of a membrane with: (a) thickness given by the *n*-type epitaxial layer and area set by the diffused *n*-well layer; (b) thickness given by *n*-type layers and area defined by the bulk etch of the silicon wafer.

2. Sensor Design

The SensoNor Multi-Project wafer service MultiMEMS was selected for the design and fabrication of the presented sensor. The MultiMEMS dice, made of one silicon wafer and two glass wafers (anodic bonded), have enough strength to cope with the pressure requirements. Considering that silicon single-crystal and polysilicon have a fracture strength not less than 1GPa [5], a membrane with a thickness of 23.1μm and a nominal area of $400\times400\mu m^2$ was selected. The membrane cavity is formed by the wet etch of the silicon wafer *p*-substrate, until the *n*-type implanted region N-WELL (electrochemical etch stop), which, given the MultiMEMS process tolerances, results in a membrane with the minimal and maximum dimensions of $378\times378\mu m^2$ and $433\times433\mu m^2$, respectively. Such a membrane design guarantees a maximum equivalent stress of 768MPa for a pressure of 10MPa (case of maximum area; $433\times433\mu m^2$), and a linearity of 0.086% between applied pressure and mechanical stress in the 0 – 1MPa range.

Fig. 2. shows the finite element analysis results for the equivalent stress and the difference between the transversal and longitudinal stresses, “Tran. - Long.”, on the membrane surface. The “Tran. - Long.” curve is an indicator of the sensitivity of a piezoresitor placed longitudinal to the nearest membrane edge, likewise, the inverse curve is an indicator of the sensitivity of a piezoresistor placed transversally to the nearest membrane edge. As shown the proposed design presents its maximum sensitivity at the membrane



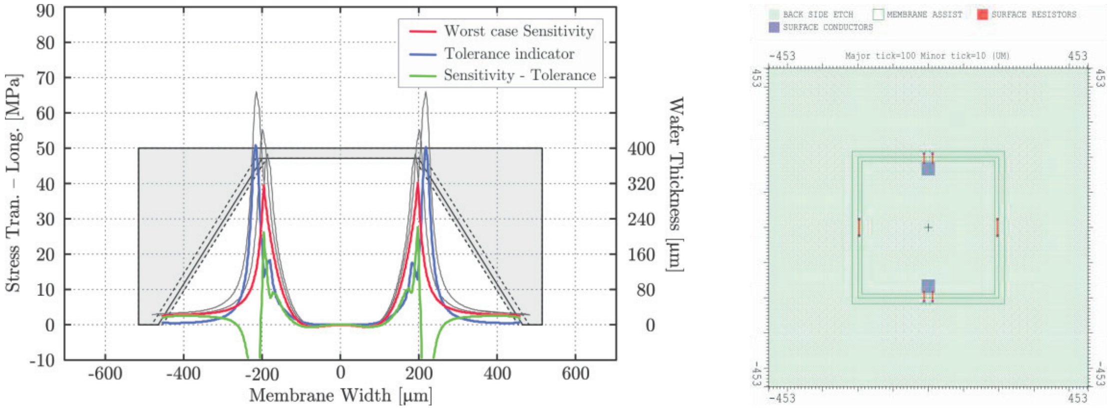
(a)

(b)

Fig. 2. Equivalent stress on the membrane surface (@ 1MPa pressure) and sensitivity indicator, “Tran. - Long.”, for a piezoresitor placed longitudinal to the nearest membrane edge: (a) over a line passing at the membrane center; (b) along the membrane edges.

edges. The sensitivity out of the membrane area is a result of the membrane edge length to thickness ratio and of the membrane cavity etched with 54.74º to the wafer surface. Indeed, the sensitivity peaks amplitude and position shifts with the membrane size, resulting in quite large variations of the sensitivity at a given point on the membrane surface (scenarios for the nominal, minimum and maximum membrane dimensions are shown in Fig. 3.(a) - grey curves). Fig. 3.(a) also shows the curve for the minimum sensitivity, guaranteed worst case value, considering the variations in the membrane area. Similarly, a tolerance indicator was found as the largest difference between all sensitivity curves. Finally, the curve “Sensitivity - Tolerance” results from the weighting of both previous measures. From this analysis, the point at 4.035µm from the membrane edge (towards its center) was found to be the best compromise between high sensitivity and low sensitivity variations, and was used for the center point of all piezoresistors used in pressure sensing.

A Wheatstone bridge of surface piezoresistors (with positive and negative sensitivity to pressure) is used to maximize the sensor sensitivity while reducing its temperature sensitivity. Since all piezoresistors are at the same temperature, the temperature coefficients of resistivity are eliminated. A temperature sensing element made of a piezoresistor was also added to the sensor die to compensate the pressure



(a)

(b)

Fig. 3. (a) Worst case sensitivity, tolerance indicator and the arithmetic weighing of both, considering the fabrication tolerances for a membrane with a nominal area of 400×400µm^2; (b) Pressure sensor masks for (cavity/membrane and sensing piezoresistors).

sensor output of the temperature coefficients of piezoresistivity. Moreover, for improved sensitivity and linearity, given the asymmetry of the stress curves (Fig. 2.), piezoresistors placed transversal to the nearest membrane edge were divided in two (Fig. 3.(b)), so that their mean sensitivity matches the one of the piezoresistors placed longitudinally to the nearest membrane edge.

3. Results

Upon fabricated, twelve sensor dice, chosen randomly from the delivered samples, were tested. The dice (fitted in TO8 packages) were placed inside a pressurized chamber, being used an AFRISO® DIN 10 gauge as pressure reference. Air was used for testing, with absolute pressures ranging from 0.01MPa to 1MPa. The sensor output was acquired with an acquisition board coupled with amplification electronics. The test results at room temperature (25ºC) for the twelve sensor dice characterized gave a mean sensitivity of 30.9mV/V/MPa with a standard deviation of 0.65mV/V/MPa and a linearity error of 0.15% of the scale span. Some samples of the presented sensor were also tested, installed in a specifically developed package, with pressures up to 10MPa keeping its characteristics and performance steady.

4. Conclusions

Considering its specifications, the pressure sensor presented achieved a very satisfactory sensitivity, which makes its use in lower pressure ranges also possible. Sensitivity variations are mainly caused by the micromachining tolerances for the membrane dimensions. Even so, a satisfactory standard deviation in sensitivity of the tested dice equal to 0.021MPa/MPa proves that the use of a 23.1µm thick membrane, with lower fabrication accuracy (dimensions are defined by the wet etching of the silicon wafer and not by the implanted layers), is practicable. Test results confirmed the high linearity of the presented sensor, which reflects the work done in the positioning and distribution of piezoresistors on the membrane surface. Moreover, the membrane design, with a small edges length to thickness ratio, also contributed for the high linearity between the applied pressure and the mechanical stress.

Overall, the sensor design performed very satisfactory. High linearity and an acceptable compromise between sensitivity and sensitivity variations were achieved, while being capable to withstand pressures up to 10MPa.

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