A design tool for pressure microsensors based on FEM simulations

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A design tool for pressure microsensors based on FEM simulations

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Abstract

The main features involved in the design of a pressure sensor are the maximum non-destructive pressure and the sensitivity. In this work, these two characteristics are related to the following design variables: dimensions of the membrane and mechanical properties of the selected material. Von Misses stress and strain distributions have been calculated by the finite-element method (FEM). The knowledge of these distributions is a good design guideline for an accurate location of the piezoresistors. The results obtained have been applied to the design of silicon microsensors for biomedical and domestic applications.

Keywords: Silicon; Microsensors; Pressure; Simulation

1. Introduction

Monolithic silicon microstructures have been applied to a wide spectrum of mechanical microsensors. Using integrated circuit manufacturing technologies and silicon micromachining techniques, comparatively low cost and small sensor sizes are achieved. Four strain gauges located in a thin membrane constitute the basis of pressure microsensors. Membrane dimensions are determined by sensor sensitivity and maximum non-destructive pressure (burst pressure). Both characteristics are related to the mechanical response of the membrane: stress and strain distributions. Mechanical behaviour of thin plates is a well-known engineering problem. An approximate method to calculate deflections and bending moments has been proposed [1]. However, no analytical expressions have been proposed to quantify burst pressure and membrane strains. Mechanical analysis of the membrane can be done by numerical methods too, such as the finite-element method (FEM) [3,7], or the finite differences method [4]. Some studies about sensitivity have been reported [2-4,6]. These methods are not simple, and they are far from design concepts. Nevertheless, to the best of the authors' knowledge, no simple expressions have been reported to calculate sensor characteristics.

In this work, burst pressure and sensitivity are related to the main sensor design parameters: the membrane thickness and area, and the mechanical properties of the bulk material (Young's modulus and Poisson ratio). A final expression is found as a design tool for pressure microsensors.

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2. Calculation method

2.1. Main characteristics of a pressure sensor

2.1.1. Sensitivity

Sensitivity is commonly defined as

$$s=\frac{V_{OUT}}{V_{IN}\Delta P} \tag{1}$$

where V_{OUT} and V_{IN} are the output and supply voltage and ΔP is the maximum applied pressure [5]. For a four-arm Wheatstone bridge, V_{OUT}/V_{IN} is related to the fractional change in resistance as follows:

$$\frac{V_{OUT}}{V_{IN}}=\frac{\Delta R}{R} \tag{2}$$

The relationship between $\Delta R/R$ and longitudinal strain (ϵ) can be expressed by means of the gauge factor:

$$GF=\frac{\Delta R/R}{\epsilon} \tag{3}$$

Combining Eqs. (1), (2) and (3) we can obtain the expression for sensitivity versus mechanical characteristics:

$$s=GF\frac{\epsilon}{\Delta P} \tag{4}$$

2.1.2. Burst pressure

Burst pressure was calculated using the Von Misses stress distribution. This is a complex criterion, and it takes account of normal and shear stresses.

2.2. *Strain and stress distributions*

The strain and stress distributions of the membrane were calculated by FEM simulations, using the COSMOS/M/ENGINEER® software [8]. Isotropic material and plane stress hypotheses were assumed. As shown in previously reported works [1,9], both are conservative hypotheses and a guarantee for a safe design. The diaphragm of the sensor was modelled meshing with square shell elements. These elements have four nodes, bending and membrane capabilities and six degrees of freedom per node. Nodes at the edges of the membrane were considered built-in. Two planes of symmetry were used to simplify the model.

2.3. *Dimensional analysis*

Data points given by FEM simulations form a numerical solution. These points were fitted using functions defined by dimensional analysis. This method allows the shape of a concrete relation to be previewed by means of the expected related variables.

2.3.1. Maximum strain (ϵ_M)

The main variables that can affect this parameter are supposed to be membrane area A [m^2], membrane thickness t [m], applied pressure P [N m^{-2}], Young's modulus E [N m^{-2}] and Poisson's ratio ν [adimensional]. Strain values are proportional to the applied pressure, as is shown in the fundamental equations of the mechanical problem [1]. As a consequence of Hooke's law, and for keeping the dimensional homogeneity $\epsilon_M \approx P/E$. On the other hand, the thicker the membrane is, the bigger the deformations will be, so:

$$\epsilon_M = K_\epsilon \frac{PA^N}{Et^{2N}} \tag{5}$$

The constants K_ϵ and N must be estimated from the FEM calculated data points. Obviously, the influence of Poisson's ratio cannot be determined, as it has no units.

2.3.2. Burst pressure (BP)

We can apply the same reasoning to the burst pressure. In this case, the main variables are membrane area A [m^2], membrane thickness t [m], fracture tensile stress σ_M [N m^{-2}], and Poisson's ratio ν [without dimension]. The expected dimensional function is

$$\mathrm{BP} = K_{BP} \frac{\sigma_M t^{2N}}{A^N} \tag{6}$$

The constants K_{BP} and N must be estimated from the FEM calculated data points.

3. Results and discussion

3.1. *FEM simulation results*

Fig. 1 shows the strain distribution of a membrane. Tensile and compressive stress zones can be identified taking into

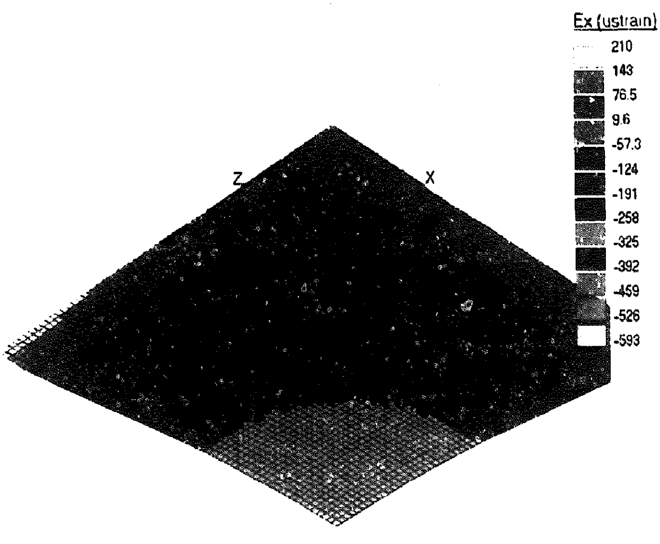

Fig. 1. Membrane ϵ_X strain distribution ($A = 1.5$ mm × 1.5 mm; $t = 15$ µm; $E = 1.862 \times 10^{11}$ Pa; $\nu = 0.27$; $P = 300$ mmHg).

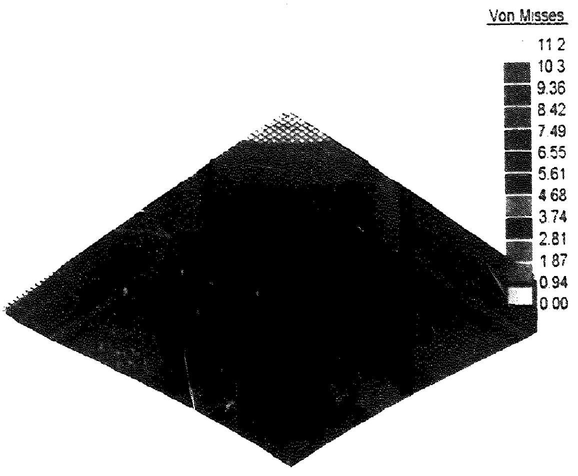

Fig. 2. Membrane Von Misses stress distribution (kg mm^{-2}) (A = 1.5 mm × 1.5 mm; t = 15 μm; $E = 1.862 \times 10^{11}$ Pa; ν = 0.27; P = 300 mmHg).

account on the sign of the deformation. Fig. 2 shows the Von Misses stress distribution. The points of maximum stress are at the middle of the membrane edges.

3.2. *Data points fit*

Figs. 3 and 4 show data points calculated from FEM simulations, and the fitted functions. The factor N is approximately equal to one. According to Eqs. (5) and (6) general functions can be written as

$$\mathrm{BP} = \frac{3.4}{1-\nu^2}\frac{\sigma_{\mathrm{MAX}}t^2}{A} \tag{7}$$

$$\epsilon_{\mathrm{M}} = 0.106(1-\nu^2)\frac{PA}{Et^2} \tag{8}$$

$$s_{\mathrm{M}} = 0.106(1-\nu^2)\mathrm{GF}\frac{A}{Et^2} \tag{9}$$

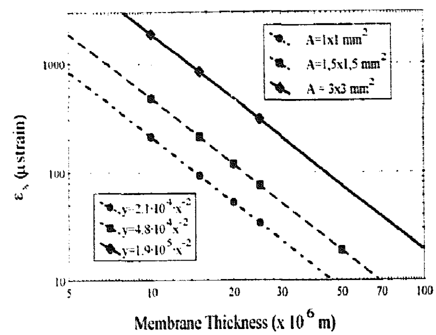

Fig. 3. Maximum tensile strain vs. membrane thickness for three different areas ($E = 1.862 \times 10^{11}$ Pa; ν = 0.27; P = 300 mmHg).

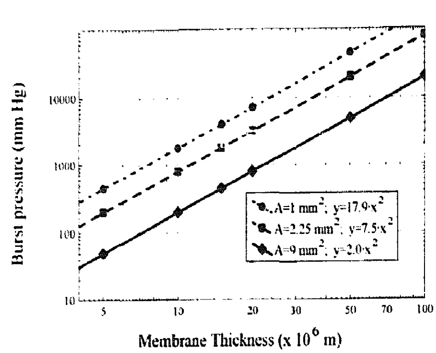

Fig. 4. Burst pressure vs. membrane thickness for three different areas ($E = 1.862 \times 10^{11}$ Pa; ν = 0.27; $\sigma_{\mathrm{MAX}} = 686 \times 10^6$ Pa).

4. Application to the design of sensors for biomedical and domestic applications

An invasive blood-pressure transducer must be able to work in the −100 to +300 mmHg pressure range, with a sensitivity of 20 μV V^{-1} mmHg^{-1}. The membrane (1.5 mm × 1.5 mm) is obtained using anisotropic etching and the electrochemical etch-stop technique. Based on exposed results, a 15 μm thick membrane is needed to achieve the desired sensitivity, supporting overpressures five times the maximum pressure.

Silicon sensors oriented to washing machines need maximum sensitivity, therefore, the thickness of the diaphragm is determined by the burst pressure. 5 μm thick membranes support overpressures of eight times the full-scale pressure (350 mmH_2O), with a sensitivity of 8 μV V^{-1} mmH_2O^{-1}. A common differential pressure of 2 mmH_2O causes a 0.0164 mV V^{-1} output, which can be detected by actual monitors.

5. Conclusions

A set of simple equations relating burst pressure and maximum strain to the main design variables has been established. An expression that allows a value of the pressure sensitivity to be estimated has been proposed. Tensile and compressive zones of the membrane have been determined by a strain distribution diagram. The points of maximum stress during pressure application have been identified. Results have been applied to the design of a microsensor for biomedical applications (−100 to +300 mmHg) and a microsensor for domestic appliances (0 to +350 mmH_2O).

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Biographies

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