A consideration of the use of ICTM SP-12 pressure sensor for ultrasound sensing

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***Abstract*— A consideration study for the application of the pressure sensor SP-12 developed and produced by ICTM CMT as an ultrasound sensor is given. The interaction of ultrasound with the sensor's membrane was analytically described, but for the initial examination of its performance, Finite Elements Method simulation was applied. The sensor SP-12 has eigenfrequencies in the range from 200 kHz to the frequencies higher than 2 MHz. The amplitude of the output signal, which is proportional to Von Mises stress, is highest for the lowest frequency, and it exponentially decreases as the eigenfrequencies increase. This makes the sensor suitable for the ultrasound measurements in the range of hundreds of kHz.**

***Index Terms*—pressure sensor; ultrasound; Von Mises stress; piezoresistor; eigenfrequencies.**

I. INTRODUCTION

Ultrasound measurement and detection have many important applications of everyday life and industry. Navigation of vehicles [1], medical examination [2], materials testing [3] and sonication (ultrasound processing of liquids) [4] are some of the applications. Sensors and detectors for ultrasound comprise different models of operation, for instance capacitive transducers [5], Fiber Bragg Grating [6] or Spherical-Omnidirectional Ultrasound Transducers [7].

One possibility for the ultrasound detection is measurement of the pressure differences it makes on the membrane of the pressure sensor. For this purpose, device originally developed as a pressure sensor can serve as an ultrasound sensor. At ICTM CMT in Belgrade, Serbia, there has been a long history of pressure sensors research and development, from the model SP-6 developed in 1980s to the model SP-12, which is currently in production [8]. This work examines possibility of application of the SP-12 pressure sensor for ultrasound sensing and gives brief overview on analytical model of membrane under mechanical stress together with numerical simulations. A proposal of experimental procedure is also given. In the presented analysis it is investigated whether the SP-12 can serve as an ultrasound sensor at the frequencies equal to its eigenfrequencies.

II. ANALYTICAL MODEL OF SP-12 MEMBRANE UNDER MECHANICAL STRESS

A. Description of sensor SP-12

The SP-12 sensor is fabricated on double-side polished single crystal n-type 3`` silicon wafer, with the resistivity of 3-5 Ωcm [8]. Four piezoresistors are formed by the photolithography process and thermal diffusion of boron at 920°C. The effective length and width of each piezoresistor are 135 μm and 5 μm, respectively. The concentration of dopants is between $1.5 \cdot 10^{20}$ cm^{-3} and $2 \cdot 10^{20}$ cm^{-3} [8].

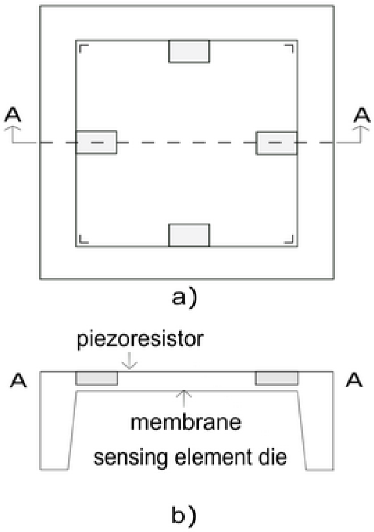

Fig 1. Schematic illustration of the SP-12 sensing element die: a) top view of the sensor; b) cross section through the middle of the diaphragm

Positions of piezoresistors on the silicon membrane are important for the sensitivity of the device. All of them are located near the edge of the membrane, two in parallel and two in the transversal direction, as it is shown in Fig. 1. They are connected in the Wheatstone bridge. The resistor positions are optimal in terms of the highest possible sensitivity and linearity of the output signal. The membrane is square of dimensions 1000 μm × 1000 μm, fabricated by wet anisotropic etching of silicon of the bottom side on the wafer [8]. The obtained thickness of the membrane is 18

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μm. Metallization is done by aluminum sputtering under the base pressure of $2\cdot 10^{-6}$ mbar. The overall size of the sensing element die is 2000 μm × 2000 μm × 380 μm [8]. After the fabrication of the die, it is anodically bonded to a 1.7 mm thick glass support [8].

B. Analytical model

The behavior of the sensor's membrane under mechanical stress was analytically modeled by using an approximation of the classical plate theory. According to this theory, differential equation for anisotropic clamped rectangular thin plate is [9]:

$$D_x \frac{\partial^4 \omega}{\partial x^4} + 2H \frac{\partial^4 \omega}{\partial x^2 \partial y^2} + D_y \frac{\partial^4 \omega}{\partial y^4} = q \qquad (1)$$

where ω is the deflection of the plate midsurface (displacement in the z direction), q is the intensity of uniform load on the plane, H is the parameter highly dependent on symmetry, and for materials with orthotropic elasticity values like single-crystal (100) silicon [10], it has a value of $\sqrt{(D_x D_y)}$ and D_x and D_y are the flexural rigidities in two orthogonal directions, and for orthotropic materials it is given by [11]:

$$D_{x/y} = \frac{E_{x/y} h^3}{12(1 - \nu_{xy} \cdot \nu_{yx})} . \qquad (2)$$

Here E is the modulus of elasticity in tension and compression, v is the Poisson's ratio and h is the plate thickness. The boundary conditions for a clamped thin plate are [9]:

$$\omega = 0, \frac{\partial^2 \omega}{\partial x^2} = 0, \frac{\partial^2 \omega}{\partial y^2} = 0, \qquad (3)$$

for $x = 0$ and $x = a$, and $y = 0$ and $y = b$, where a and b indicate the plate edge lengths. In other words, the bending moment at the edge of the membrane is zero. For the square plate, a and b are equal. If the load q is represented in the form of a double trigonometric series, a solution of the differential equation (1) can be presented in the form of [9]:

$$\omega = \sum_{m=1,3,5...}^{\infty} \sum_{n=1,3,5...}^{\infty} a_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} . \qquad (4)$$

By substituting this solution in Eq. (1), the expression for coefficients a_{mn} is found. In the case of uniform load the deflection surface is symmetrical with respect to the axes $x = a/2$ and $y = b/2$. For that reason all terms with even numbers for m or n in series (4) do not exist. Hence, the final solution of Eq. (1) is [9]:

$$\omega = \frac{16q}{\pi^6} \sum_{m=1,3,5...}^{\infty} \sum_{n=1,3,5...}^{\infty} \frac{\sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}}{mn\left(\frac{m^4}{a^4} D_x + \frac{2m^2 n^2}{a^2 b^2} H + \frac{n^4}{b^4} D_y \right)} . \qquad (5)$$

For orthotropic (100) silicon membrane, values of the modulus of elasticity are $E_x = E_y = 169\ GPa$ [12], while the values of the Poisson's ratio, when the extension is applied along x, i.e. y direction, are $\nu_{xy} = \nu_{yx} = 0.064$ [12]. By including these values in Eq. (2), flexural rigidities D_x and D_y are calculated to be $8{,}25\cdot 10^{-5}\ Pa\cdot m^3$. We assume that amplitude of the ultrasound pressure is 100 Pa. Deflection at the center of the orthotropic plate with $a = b$ and $D_x = D_y$ can be expressed by the formula [9]:

$$\omega = 0.00407 \cdot \frac{q \cdot b^4}{D_y}, \qquad (6)$$

and is estimated to *4,9 nm*. It is important to mention that this calculated deflection refers to the membrane's center when static pressure is applied. That means resonant frequency (eigenfrequency) contribution is not included in the calculation. In order to obtain values of deflection for membrane's resonant frequency when harmonic perturbation like ultrasound is applied, further analysis is needed, whose complexity overcomes the scope of this paper.

III. Finite Elements Method model of eigenfrequencies

The eigenfrequencies of the SP-12 membrane can be found from the FEM model by solving the eigenvalue problem that arises from the equations if velocity is considered to be unknown. A standard matrix form of the dynamic equation of motion can be written as [13]:

$$[M]\frac{d^2 y}{dt^2} + [B]\frac{dy}{dt} + [K]y = 0, \qquad (7)$$

where y is the vector of nodal displacement under the external force vector, and [M], [B] and [K] are the element matrices for mass, damping and stiffness for the whole structure. Under free vibration, the eigenfrequencies and the mode shapes of a multiple degree of freedom system are the solutions of the eigenvalues problem.

FEM codes are designed to solve systems of equations like Eq. (6), with one equation for each of the relevant planes. It is possible to determine the eigenvalues and eigenvectors after integrating the approximate solution and forming the matrices.

The finite element modeling was performed using COMSOL Multiphysics software [14] which provides data about the interaction between the ultrasound and silicon membrane. A quarter of the whole tested diaphragm is chosen for the model and appropriate boundary conditions and symmetry are defined in order to simplify the construction of the model and subsequent calculation. The intensity of ultrasound pressure in boundary load is set to value of 100 Pa. In order to obtain structural response of harmonic load on membrane, Frequency Domain Study was applied. Range of ultrasound frequencies is selected to include the values of the eigenfrequencies, obtained as results of Eigenfrequency Analysis performed before the mentioned study. The maximum of displacements and Von Mises stresses appear on frequencies values that correspond to the eigenfrequencies of the tested membrane.

Results of the simulation are shown in Figs. 2-6 for the first five eigenfrequencies. Values of Von Mises stresses are listed in the Table 1 only for the positions of interest, which coincide with position of SP-12 piezoresistors. These positions are marked in Figs. 2-6 with the white arrows.

TABLE I
NUMERICAL RESULTS OF THE SIMULATION

eigenfrequency (Hz)	Von Mises stress (Pa)	membrane central point amplitude (μm)
$2.59 \cdot 10^5$	$1.13 \cdot 10^9$	10.89
$9.35 \cdot 10^5$	$8.45 \cdot 10^8$	1.03
$9.39 \cdot 10^5$	$4.45 \cdot 10^7$	0.59
$1.55 \cdot 10^6$	$4.06 \cdot 10^6$	$36 \cdot 10^{-3}$
$1.80 \cdot 10^6$	$1.72 \cdot 10^5$	$44 \cdot 10^{-6}$

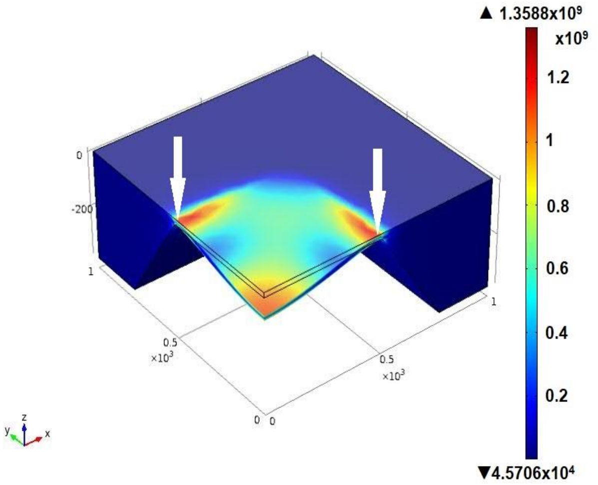

Fig 2. Mode shape of tested silicon membrane for eigenfrequency $2.59 \cdot 10^5$ Hz

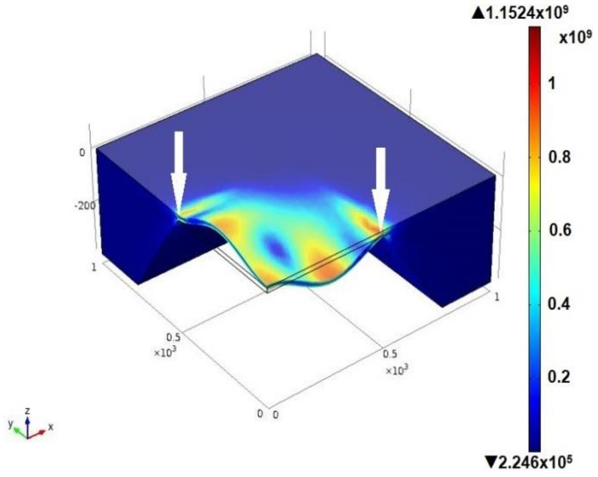

Fig 3. Mode shape of tested silicon membrane for eigenfrequency $9.35 \cdot 10^5$ Hz

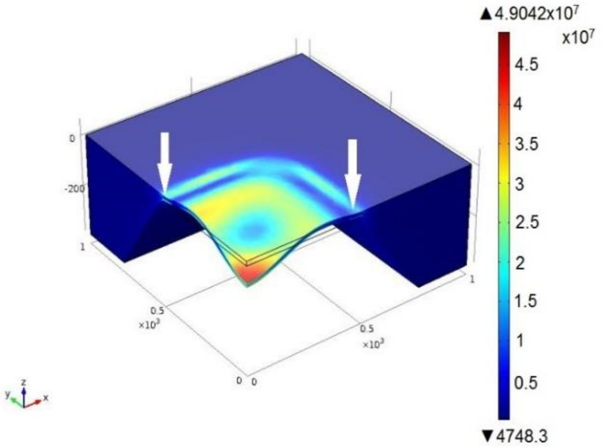

Fig 4. Mode shape of tested silicon membrane for eigenfrequency $9.39 \cdot 10^5$ Hz

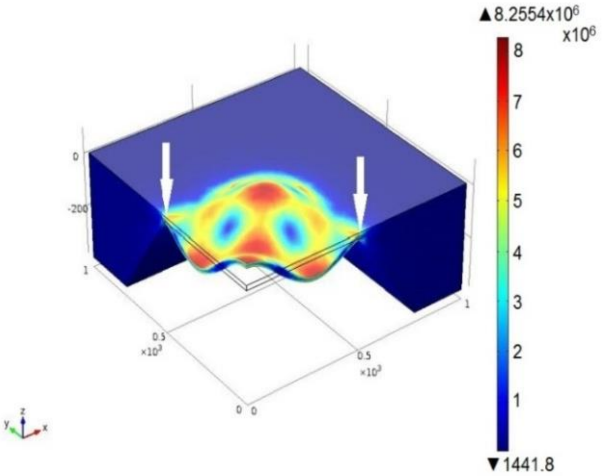

Fig 5. Mode shape of tested silicon membrane for eigenfrequency $1.55 \cdot 10^6$ Hz

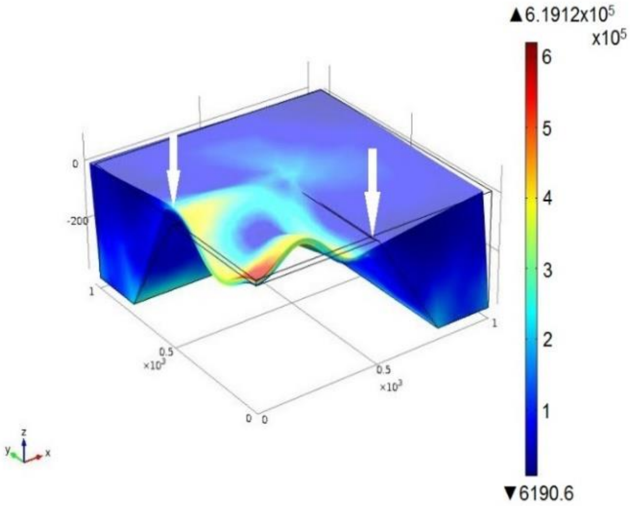

Fig 6. Mode shape of tested silicon membrane for eigenfrequency $1.80 \cdot 10^6$ Hz

IV. PROPOSAL OF THE EXPERIMENT

In the proposed experimental set-up (Fig. 7), the ultrasound source will be a specifically shaped material from the group of piezoelectric ceramics. The SP-12 sensor will be connected to a constant current source which provides the excitation current of 5 mA. The output of the SP-12 sensor is connected to a spectrum analyzer. A maximum amplitude position in a digital record of the analyzer is expected to coincide with simulation results from Comsol. A potential problem of the experimental set-up would be the choice of the appropriate ultrasound source, whose range of soundwave frequencies should also include the resonant frequencies of the tested silicon membrane.

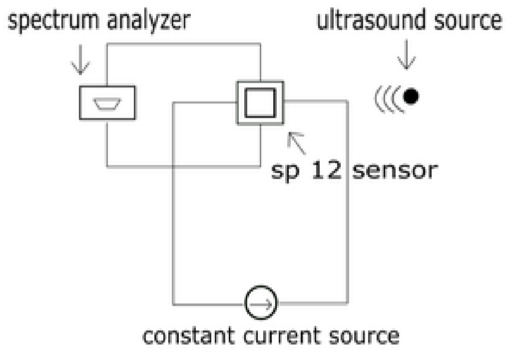

Fig 7. Schematic illustration of the proposed experiment

V. CONCLUSION

The purpose of this consideration study, was to examine the suitability of the ICTM CMT pressure sensor SP-12 for ultrasound detection. The interaction of mechanical pressure with the sensors's membrane was analytically described and numerically simulated. It was shown that this type of sensor has a potential to be used as ultrasound sensor. The range of ultrasound frequencies that can be probed corresponds to the silicon membrane eigenfrequencies.

It was noticed that stress at the positions of the piezoresistors has the highest value for the first two mode shapes. Therefore, eigenfrequencies that correspond to those mode shapes will be of our interest for the future ultrasound detection and measurement. Experimental testing is in preparation, where SP-12 will be connected in electrical circuitry in the similar way as pressure sensor, but the read-out will be performed by spectrum analyzer. The degree of agreement between analytical and numerical predictions with the experimental results will be investigated.

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REFERENCES

[1] J. Hyo Rhee and J. Seo, "Low-Cost Curb Detection and Localization System Using Multiple Ultrasonic Sensors," *Sensors*, vol. 19, 21 March 2019.

[2] T. L. Szabo, "*Diagnostic Ultrasound Imaging: Inside Out Biomedical Engineering*," 2th ed. revised Academic Press, ISBN 9780123965424, 2013.

[3] C. H. Chen, "*Ultrasonic And Advanced Methods For Nondestructive Testing And Material Characterization*," University of Massachusetts, USA, World Scientific, ISBN 9814476404, 2007.

[4] J. L. Capelo-Martínez, "*Ultrasound in Chemistry: Analytical Applications*," Wiley-VCH Verlag GmbH & Co. KgaA, Weinheim, Germany, ISBN 978-3-527-31934, 2009.

[5] A. Pirouz and F. Levent Degertekin, "An Analysis Method for Capacitive Micromachined Ultrasound Transducer (CMUT) Energy Conversion during Large Signal Operation Sensors," *Sensors*, vol. *19*, 20 February 2019.

[6] Ch. Rao and L. Duan, "Bidirectional, Bimodal Ultrasonic Lamb Wave Sensing in a Composite Plate Using a Polarization-Maintaining Fiber Bragg Grating," *Sensors*, vol. *19*, 19 March 2019.

[7] S. Sadeghpour, S. Meyers, J. P. Kruth, J. Vleugels, M. Kraft and R. Puers, "Resonating Shell: A Spherical-Omnidirectional Ultrasound Transducer for Underwater Sensor Networks," *Sensors*, vol. *19*, 13 February 2019.

[8] M. Frantlović, I. Jokić, Ž. Lazić, M. M. Smiljanić, M. Obradov, B. Vukelić, Z. Jakšić and S. Stanković, "A method enabling simultaneous pressure and temperature measurement using a single piezoresistive MEMS pressure sensor," *Meas. Sci. Technol.* vol. *27*, 21 October 2016.

[9] S. Timoshenko, S. Woinowsky-Krieger, "Bending of Anisotropic Plates" in *Theory of plates and shells*, 2th ed. McGraw-Hill Book Company, USA, ISBN 0-07-064779-8, 1989.

[10] Z. Qin, Y. Gao, J. Jia, X. Ding, L. Huang and H. Li, "The Effect of The Anisotropy of Single Crystal Silicon on the Frequency Split of Vibrating Ring Gyroscopes," *Micromachines*, vol. *10*, 14 February 2019.

[11] A. F. Johnson and A. Woolf, "Deflection and stress analysis of orthotropic plates in flexure," *Computers & Structures*, vol. *18*, pp *911-919*, 1984.

[12] E. V. Thomsen, K. Reck, G. E, Skands, C. V. Bertelsen, O. Hansen, "Silicon as anisotropic mechanical material: Deflection of thin crystal planes," *Sensors and Actuators A: Physical*, vol. *220*, pp. *347-364*, 2014.

[13] A. Belhadj, R. Cheesewright and C. Clark, "The simulation of coriolis meter response to pulsating flow using a general purpose F. E. code," *Journal of Fluids and Structures*, vol. *14*, pp. *613-634*, 2000

[14] Comsol software https://www.comsol.com/ Accessed 18.1.2019.