ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 14, No. 2. 2008

Investigation of Dynamic Parameters of Multilayered Microelectromechanical Membranes with Finite Element Modeling

Gailius VANAGAS[1,2], Marius MIKOLAJŪNAS[1,2], Viktoras GRIGALIŪNAS[1,3], Renata JARIMAVIČIŪTĖ-ŽVALIONIENĖ[3], Algis IVAŠAUSKAS[1,2], Darius VIRŽONIS[1,2] *

[1]*UAB Minatech, Savanorių 271, LT-50131 Kaunas, Lithuania*
[2]*Kaunas University of Technology Panevezys Inst., Department of Electric Engineering, Daukanto 12, LT-35212, Panevėžys, Lithuania*
[3]*Institute of Physical Electronics, Kaunas University of Technology, Savanorių 271, LT-50131 Kaunas, Lithuania*

Received 24 October 2007; accepted 01 March 2008

Static and dynamic parameters of cMUT cells with layered membranes were investigated using finite elements modeling. It was found that introducing porous silicon in the middle layer of the thin films stack, forming the membrane of the cell, creates an opportunity to operate the cell at more favourable energetic conditions: the excitation voltage can be decreased by 30 %, if porous silicon with 0.5 filling factor is introduced in the middle layer of the membrane. Approximately the same or better increase of receiving sensitivity was also found. Harmonic analysis showed an increase of the electric impedance of the cell with layered membranes at the resonance frequency up to the factor of 2 with simultaneous decrease of the resonance frequency by approximately 0.6 MHz.
Keywords: capacitive micromachined ultrasound transducer, finite element modeling, porous silicon.

INTRODUCTION

Surface micromachining technique is an attractive opportunity for manufacturing microelectromechanical systems (MEMS). However, this technique meets difficulties when is used to machine membrane shaped microstructures. Particularly, material engineers are facing the problem of etching the sacrificial material in comparatively large areas (commonly 800–1000 square microns) through comparatively narrow etching vias (up to several square microns of cross section area) [1]. This requires exceptionally good etching selectivity during the sacrificial layer etching, which is achieved using silicon nitride as a structural material and polycrystalline silicon [1] or metals [2] for sacrificial layer. On the other hand, improving the etching selectivity is often related with the increased stress gradients between the structural material and the sacrificial layer, which makes release of membranes larger than 160 μm nearly impossible [1].

Plasma enhanced chemical vapor deposition (PECVD) technique, if used with dual frequency plasma, is suitable for producing dense silicon nitride films with desirable stress values [3]. However, film densification may affect the functionality of the device, as the moving mass of the dense film is greater and influences dynamics of the system [4, 5]; controversially, reducing the thickness and (or) density of the structural material may reduce the reliability and mechanical robustness of the system. Therefore in this work we explored the potential of stacking the layers of materials with different properties, where outside layers of the stack are devoted for mechanical robustness, chemical inertia and electrical insulation, and the inside material is porous, compensating for intrinsic stress and for increased mass of the moving parts. With this computer simulation work we continue our earlier experimental investigation [6].

Multilayered film stack commonly results, when some protective layers are formed over the devices [4, 7]. Stacked films are also used for adjustment of intrinsic stress in thin film structures [6]. However, the potential of adjusting dynamic parameters of devices, when the stack of different thin film materials is used to form the functional parts of MEMS instead of bare film, remains unexplored. Therefore the aim of this research was to evaluate these parameters experimentally and explore them with computer simulation.

METHODS AND REFERENCE MATERIALS USED

We used 3D finite element method (FEM) modelling of a single capacitive ultrasound transducer (cMUT) cell [4, 8], immersed in fluid (Fig. 1). The membrane was modeled as three layer structure, where the properties of an outside layers was kept constant (specific for PECVD silicon nitride), and the properties of the middle layer (porous silicon as a reference material) was varied to determine possible range of the device's functional parameters. Each of the membrane layers was divided by SOLID45 elements, the vacuum gap – by TRANS126 elements. The ambient medium was modelled as hemisphere, consisting of FLUID30, with FLUID130 at the hemisphere edge. The last is introduced to prevent the ultrasound reflections from the medium boundary. For completeness of the results, a gold top electrode and protective film (PECVD silicon nitride) were also included to the model. The main model parameters are shown in Table 1. Porous silicon is an interesting material, because the number, size and density of pores can vary in a wide range. Common parameter when characterizing the porosity is the filling coefficient [9, 10], which in our case

*Corresponding author. Tel.: + 370-45-434247; fax.: + 370-45-516161.
E-mail address: *darius.virzonis@ktu.lt* (D. Viržonis)

Table 1. Main parameters of FEM model

Parameter	Dimension	Material
Membrane radius	19 µm	–
Top layer thickness	0.1 µm	Si_3N_4
Middle layer thickness	0.3 µm	porous silicon
Bottom layer thickness	0.1 µm	Si_3N_4
Vacuum gap	0.2 µm	–
Isolating layer thickness	0.15 µm	Si_3N_4
Top electrode radius	15 µm	–
Top electrode thickness	0.1 µm	Au
Protective layer thickness	0.3 µm	Si_3N_4

Materials properties [11]	Si	Si_3N_4	Au
Elasticity modulus, GPa	150	200	75
Poisson coefficient	0.17	0.24	0.42
Density, kg/m^3	2332	3200	19300

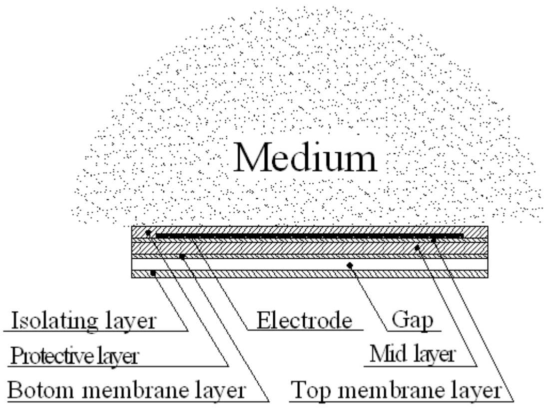


Fig. 1. Structure of the FEM model

was modelled in the range from 0.5 to 0.9. We found this range reasonable after experimental analysis of conditions at which the porous silicon still preserves its integral structure. Common structure of porous silicon with marked area, which was supposed to represent the middle of the reasonable porosity range, is shown in the scanning electron microscope picture in Fig. 2.

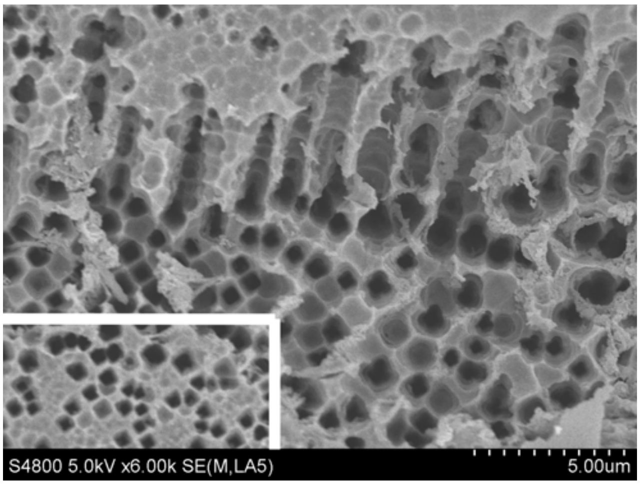


Fig. 2. Scanning electron microscope picture of porous silicon. The rectangle at the left bottom angle shows the 24.64 µm^2 area with 4.9 µm^2 pores area, which corresponds to the filling coefficient of 0.8

It is very important that elasticity modulus varies with porosity too. According to [11], elasticity modulus of porous silicon can be calculated by the following equation:

$$\frac{E_p}{E_s} = C\left(\frac{\rho_p}{\rho_s}\right)^2, \tag{1}$$

where E_s is the elasticity modulus of bulk material, E_p is the elasticity modulus of porous material, ρ_s is the density of porous material, ρ_p is the density of bulk material. C is a material-dependent coefficient, which can be held close to 1 in our case [9 – 11].

The porous silicon density ρ_p was calculated by multiplying density of bulk silicon ρ_p by the filling coefficient. The density and elasticity of middle layer were the actual arguments alternated during modelling in order to determine their influence to the performance of the cMUT cell.

In dynamic modelling the membrane bias voltage was always kept constant at 0.8 of the collapse voltage, and the initial constant pressure in the medium was held at 0.1 MPa.

MODELING CONDITIONS AND RESULTS

Static parameters. The most important static parameters of cMUT is the membrane displacement performance (static electromechanical transfer function for transmission) and the capacitance performance (static electromechanical transfer function for receiving). The membrane displacement performance (obtained during modelling) for different filling factors of middle membrane layer, is shown on Fig. 3. In all the cases simulation was ended with reaching the collapse voltage [12].

The changes in cell capacitance follow the changes of the applied voltage. It is shown in Fig. 4. The steep increase in capacitance after the collapse voltage is reached, is followed by the further slow increase due the increasing contact area between the substrate and membrane.

When calculating the capacitance, we used one of the the outputs of the FEM model for the displacement: the cumulative energy in cMUT capacitor E_C, which then was

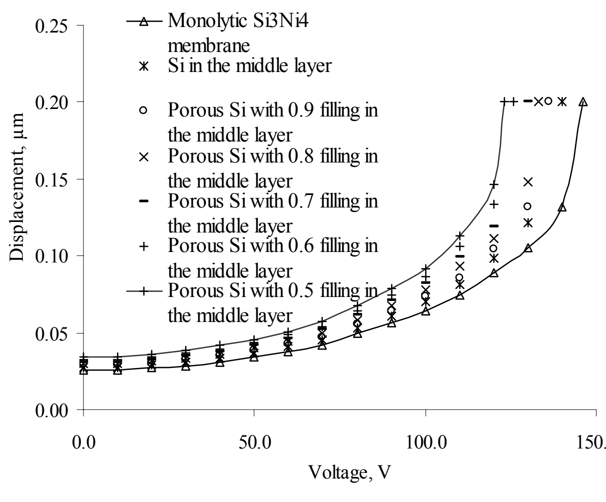


Fig. 3. Displacement of the centre point of the membrane as a function of applied voltage and porosity of the silicon in the middle layer. Ambient pressure is 0.1 MPa in all cases

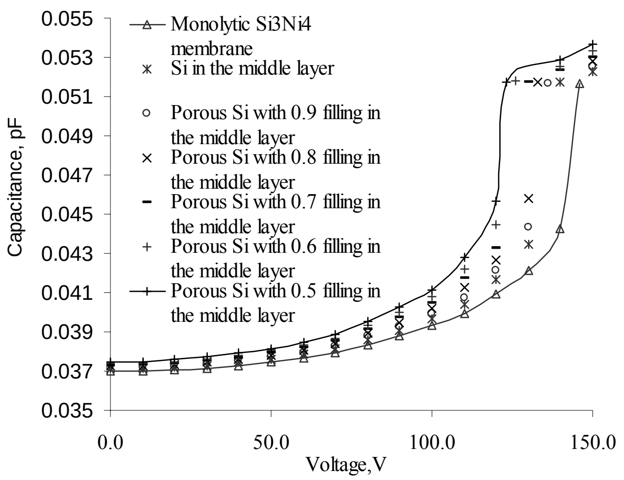


Fig. 4. Response of the cell capacitance to the applied voltage

converted to capacitance, using a following fundamental equation:

$$C = \frac{2E_C}{U^2}. \tag{2}$$

Here U is the voltage applied to the capacitor.

This method to find the capacitance is advantageous over the methods published earlier [12], because it does not involve any additional segmentation of the membrane, and therefore saves the modelling time. The capacitance performance for receiving is show in Fig. 5 as a cell capacitance response to the pressure in ultrasound transmission medium.

All the static characteristics obtained show the energetically favourable conditions for the layered membrane. The greater is the porosity of the middle layer, the lower the voltage is needed for the same deflection of the membrane, and the lower pressure in the ultrasound transmission medium is needed to change the capacitance.

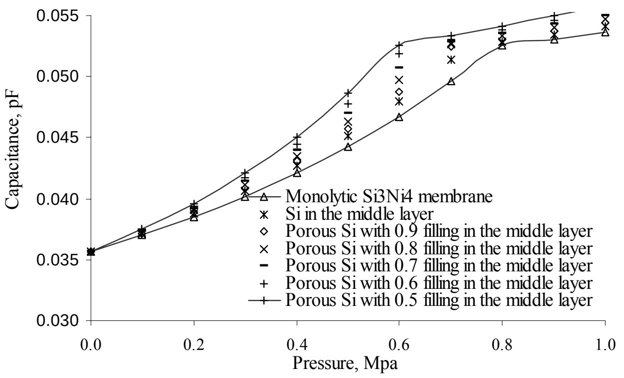
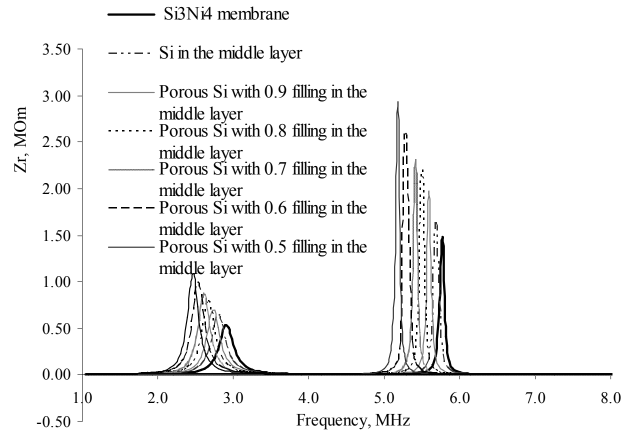
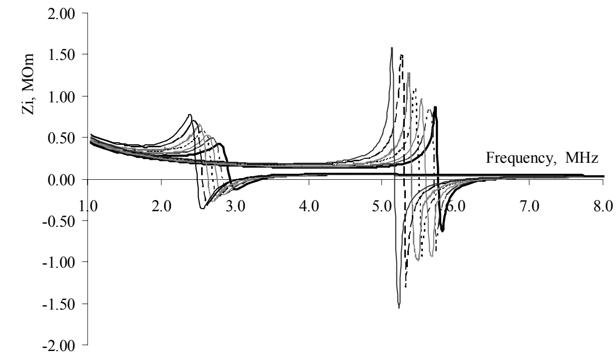


Fig. 5. Response of the cell capacitance to the pressure in the ultrasound transmission medium

Practically this means the potential for reducing the excitation voltage by approximately 30 % and increase of the receive sensitivity for the same or greater amount. As an example, instead of operating the membrane (made of monolithic Si_3N_4) with 100 V, it can be operated by 70 V, the cell capacitance change with increase of the pressure in the medium from 0 MPa to 0.3 MPa for monolithic Si_3N_4 membrane is the same as from 0 MPa to 0.2 MPa for the membrane with the porous silicon of 0.5 filling in the middle layer.



a



b

Fig. 6. Calculated electrical impedance of the single cMUT cell: a – real part; b – imaginary part. Right resonance (from 5 MHz to 6 MHz) corresponds to the oscillation in vacuum and the left resonance (from 2 MHz to 3 MHz) corresponds to the water immersion conditions

Dynamic parameters. One of the most important dynamic parameters is the harmonic response of the membrane, which is commonly characterized by the electrical impedance at the resonance frequency region [12, 13]. We calculated the electrical impedance as described by Yaralioglu et. al. [12], i. e. small amount of losses was introduced in harmonic analysis model to have contour quality close to the experimentally determined value. Here we relayed to the experimental knowledge published by the above mentioned authors, however, in our case the damping losses can be slightly different in each case due the varying porosity of the middle layer. This was neglected in our simulation due the absence of experimental data in each particular case. To convert the output parameter of FEM model (equivalent dynamic displacement d_p) to an impedance value we used the equation published by Ballandras et. all. [13]:

$$Z = \frac{\operatorname{Im} d_p}{\omega \varepsilon_0 S} + j\frac{d - \operatorname{Re} d_p}{\omega \varepsilon_0 S}. \tag{3}$$

Here d is an initial gap between the top electrode and the substrate, S is the area of the top electrode and ε_0 is the dielectric constant of a vacuum.

The real and imaginary parts of the calculated impedance are shown in Fig. 6, a and b correspondingly. Two resonances at different conditions are shown: rightside resonance corresponds to the membrane oscilating in vacuum, and the left-side resonance results if the membrane is immersed in water.

The modelling results show the tendency to lower the resonance frequency and increase the amplitude of oscillations with increasing porosity (decreasing filling) of the middle layer of the membrane. An increasing oscillation amplitude counts for increased sensitivity, however the lower resonance frequency is to be considered during the transducer design process.

As a derivation of above commented results we also modelled the frequency response of an array of cMUT cells, which consists of evenly distributed three types of cells, having differently filled porous silicon in the middle layer, namely 0.5, 0.7 and 0.9. The cummulative response was calculated by the integration of corresponding frequency responses. Resulting frequency response is shown in Fig. 7. Here the broadening of the frequency response is the main result. It is desirable, when working with the short ultrasonic pulses (they are common in echoscopy and other ultrasonic applications) because it enlarges the fractional bandwidth, what is one of the main advantages of cMUT's [1, 14, 15].

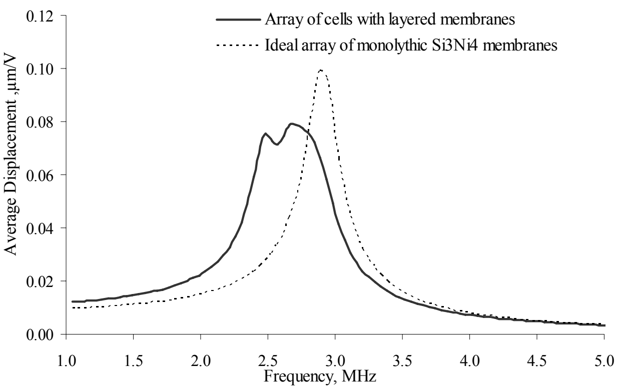


Fig. 7. Calculated frequency response of two cMUT arrays. One of them consists of evenly distributed cels of three types of the midle layer (porous silicon with 0.5, 0.7 and 0.9 filling; solid line) and the ideal array with membranes consisting of monolythic Si_3N_4 (dashed line)

CONCLUSIONS

During the static analysis we found that cMUT cells with layered membranes, having porous silicon with 0.5 filling factor in the middle layer, are potentially able to be operated with the excitation voltage 30 % less than ordinary cells with monolithic Si_3N_4 membranes. Correspondingly, the receive sensitivity of such a cells is to be increased by the same or greater amount.

Harmonic analysis showed an increase of the electric impedance of the cell with layered membranes at the resonance frequency up to the factor of 2 (Fig. 6) with simultaneous decrease of the resonance frequency by approximately 0.6 MHz. Although increase of the oscillation amplitude is an advantage, resonance frequency changes have to be considered during the transducer design.

Acknowledgements

This research was supported by the Lithuanian State Science and Study foundation. It is also the part of the research under the grant from EU structural funds, contract No BPD2004-ERPF-3.1.7-06-06/0029.

REFERENCES

1. **Ergun, A. S. et al.** Capacitive Micromachined Ultrasonic Transducers: Fabrication Technology *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions* 52 2005: p. 2242.
2. **Cianci, E. et al.** Improvements Towards a Reliable Fabrication Process for cMUT *Microelectronic Engineering* 67–68 2003: p. 602.
3. **Cianci, E. et al.** Dual Frequency PECVD Silicon Nitride for Fabrication of CMUTs' Membranes *Sensors and Actuators A: Physical* 127 2006: p. 80.
4. **Vanagas, G. et al.** FEM Simulation of the Harsh Environment cMUT Design *Proceedings of the 6th International Conference Vibroengineering 2006* 2006: p. 203.
5. **Manoj, K. K. M. et al.** Effect of Mass Damping and Stiffness Damping in Micromachined Air Coupled Capacitance Transducer *In: Thompson DO, Chimenti DE, editors. Review of Progress in Quantitative Nondestructive Evaluation* Vols 26a and 26b Vol. 894 2007: p. 870.
6. **Mikolajūnas, M. et al.** Study of Stacked PECVD Silicon Nitride Films Used for Surface Micromachined Membranes *Thin Solid Films* 2008 (submitted).
7. **Sabate, N. et al.** Mechanical Characterization of Thermal Flow Sensors Membranes *Sensors and Actuators A: Physical* 125 2006: p. 260.
8. **Ronnekleiv, A.** CMUT Array Modeling Through Free Acoustic CMUT Modes and Analysis of the Fluid CMUT Interface Through Fourier Transform Methods *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions* 52 2005: p. 2173.
9. **Bellet, D., Lamagnere, P., Vincent, A., Brechet, Y.** Nano-indentation Investigation of the Young's Modulus of Porous Silicon *Journal of Applied Physics* 80 1996: p. 3772.
10. **Lee, D. et al.** Microfabrication and Mechanical Properties of Nanoporous Gold at the Nanoscale *Scripta Materialia* 56 2007: p. 437.
11. **Gibson, L. J., Ashby, M. F.** Cellular Solids: Structure and Properties. Cambridge: Cambridge University Press, 1997.
12. **Yaralioglu, G. G., Ergun, S. A., Khuri-Yakub, B. T.** Finite-element Analysis of Capacitive Micromachined Ultrasonic Transducers *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions* 52 2005: p. 2185.
13. **Ballandras, S. et al.** Periodic Finite Element/Boundary Element Modeling of Capacitive Micromachined Ultrasonic Transducers *Journal of Applied Physics* 97 2005: 034901.
14. **Xuecheng, J. et al.** Fabrication and Characterization of Surface Micromachined Capacitive Ultrasonic Immersion Transducers *Microelectromechanical Systems* 8 1999: p. 100.
15. **Demirci, U. et al.** Forward-viewing CMUT Arrays for Medical Imaging *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions* 51 2004: p. 887.

Presented at the National Conference "Materials Engineering'2007"
(*Kaunas, Lithuania, November 16, 2007*)