Influence of Geometrical Configuration of Cantilever Structure on Sensitivity of MEMS Resonant Sensors

Georgeta Ionascu[1], Adriana Sandu[2], Elena Manea[3], Lucian Bogatu[4]

[1] *Professor, Mechatronics & Precision Mechanics Dpt., POLITEHNICA University of Bucharest, Romania*
[2] *Professor, Strength Materials Dpt., POLITEHNICA University of Bucharest, Romania*
[3] *Dr., National Institute for Research & Development in Microtechnology of Bucharest, Romania*
[4] *Lecturer, Mechatronics & Precision Mechanics Dpt., POLITEHNICA University of Bucharest, Romania*

---***---

Abstract - *In this paper, modeling, simulation and an experimental study of two MEMS structures of microcantilever, with triangular and trapezoidal shape, are presented. A numerical computation model using Finite Element Method (FEM) has been developed to simulate the behaviour of these micro-beams, in static and dynamic regime. The obtained theoretical results have been experimentally validated through LDV (Laser Doppler Vibrometry) method.*

Key Words: **micro-beams, MEMS sensors, spring constant, dynamic computation**

1. INTRODUCTION

As their name suggests, the resonant MEMS sensors (sensing Micro-Electric-Mechanical Systems) are devices that measure physical phenomena using oscillations. More exactly, a resonant MEMS sensor contains a micromechanical structure designed to reach a certain resonant frequency depending on a certain external physical parameter. When this parameter changes, a variation of the structure's resonant frequency is produced, variation which is measured and correlated analitically, numerically and experimentally with the variation of physical parameter value.

The electromechanical nature of MEMS structures involves that the mechanical oscillations affect the electric properties of devices, too. Consequently, a physical parameter is converted by means of mechanical oscillations of the structure into an electric signal, which can be read in several ways.

In time, several models of MEMS resonators were created and tested. Although each of these structures is unique and original, the most of them are based on three general designs: cantilevers, doubly clamped "bridge" beams and folded flexure beams [1].

The sensitive elements of microcantilever type are the simplest structures, both as a utilization and as fabrication. The micro-beam is anchored at only one end to the substrate. When it is acted, the free end oscillates in perpendicular direction on the device layout. This sensitive element has multiple advantages, such as:

- a simple fabrication process, with reduced costs; the fabrication process typically involves undercutting the cantilever structure to release it from substrate (the silicon wafer), often with an anisotropic wet or dry etching technique [2];
- in monobloc construction, there are no residual stresses, which makes the modes of vibration to be known and easily described using mathematical models [3].

The cantilever structures are interesting in applications of biological and chemical sensors with high sensitivity (for instance, the flexible trapezoidal shape), as well as in atomic force microscopy (the stiff triangular shape) due to higher modes, useful for development of new imaging modes.

In this paper, modeling, simulation and an experimental study of two MEMS structures of microcantilever, with triangular and trapezoidal shape, are presented. The static and dynamic behaviour of these micro-beams has been studied. For this purpose, a numerical computation model, with finite element method, has been developed. The spring constant and the resonant fundamental frequency for the two analysed geometrical configurations have been determined. The obtained results were experimentally validated using LDV method.

2. THE STUDIED STRUCTURES

n – (111) silicon wafers (Fig -1) of 3 inch diameter and 375 μm thickness were thermally oxidized in wet oxygen atmosphere to obtain a silicon dioxide (SiO_2) layer of about 1.7 μm thickness, used both as protective layer (mask) during etching process, and as constructional material for cantilevers after releasing from substrate (the silicon wafer).

The oxide layer was photo-etched by means of a standard photolithographic technique, followed by etching in an HF – solution. In a first stage, in the opened windows, the silicon was plasma etched through a Bosch process using a DRIE (Deep Reactive Ion Etching), Fig -2 – Plasmalab System 100-ICP (Inductively Coupled Plasma) to a depth of about 40 μm. Two steps were performed: (1) a passivation process to 100 sccm flow rate of C_4F_3, and (2) an etching process to 100 sccm

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 03 Issue: 12 | Dec -2016 www.irjet.net p-ISSN: 2395-0072

flow rate of SF_6; working pressure 10 mTorr at 15 °C, power in RF 5 W, ICP power 700 W and etch rate of 2 – 3 µm/min. So, on the silicon surface from the vertical walls of the etched cavities, the access to the faster etching (110) crystal planes was allowed in order to perform a second etching stage (wet etching), based on the anisotropy of silicon.

Potassium hydroxide (KOH) 40% at 80 °C (lateral etch rate of about 100 µm/h along the <110> direction) was employed to release the SiO_2 cantilevers from the wafer surface. Two structures types were created: triangular – "V shaped" and inner-cut trapezoidal with rectangle tip cantilevers, as is shown in Fig -3 and Fig -4, respectively.

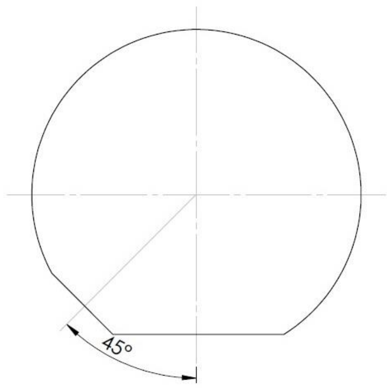

Fig -1: n – (111) silicon wafer, used as substrate for the SiO_2 structures of cantilever type

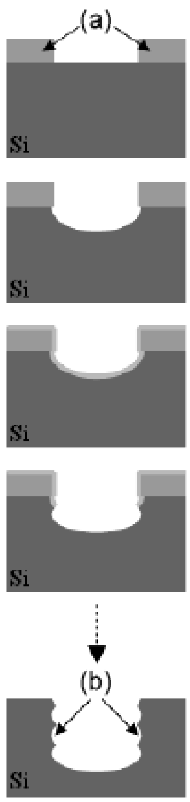

Fig -2: Example of plasma etching by the Bosch process (a – protective layer, b – vertical sidewalls)

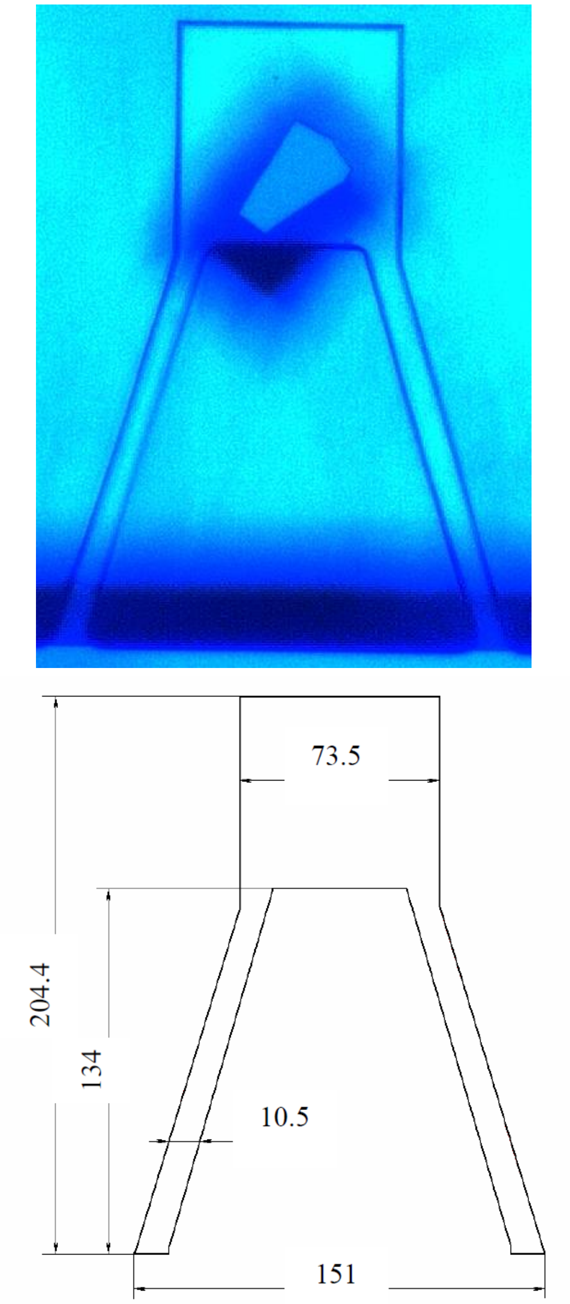

Fig -3: The cantilever beam of *trapezoidal* shape after releasing from the silicon wafer – image on optical microscope. The dimensions from the sketch are given in µm. The structure thickness is SiO_2 layer thickness (1.7 µm)

The material properties used in static and dynamic calculation of the structures are presented in Table -1.

Table -1: Material properties for the numerical calculations

Material	SiO_2
Young' Modulus, *E* (MPa)	$7 \cdot 10^4$
Poisson's Ratio, *ν* (-)	0.17
Density, *ρ* (kg/m³)	2200

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 03 Issue: 12 | Dec -2016 www.irjet.net p-ISSN: 2395-0072

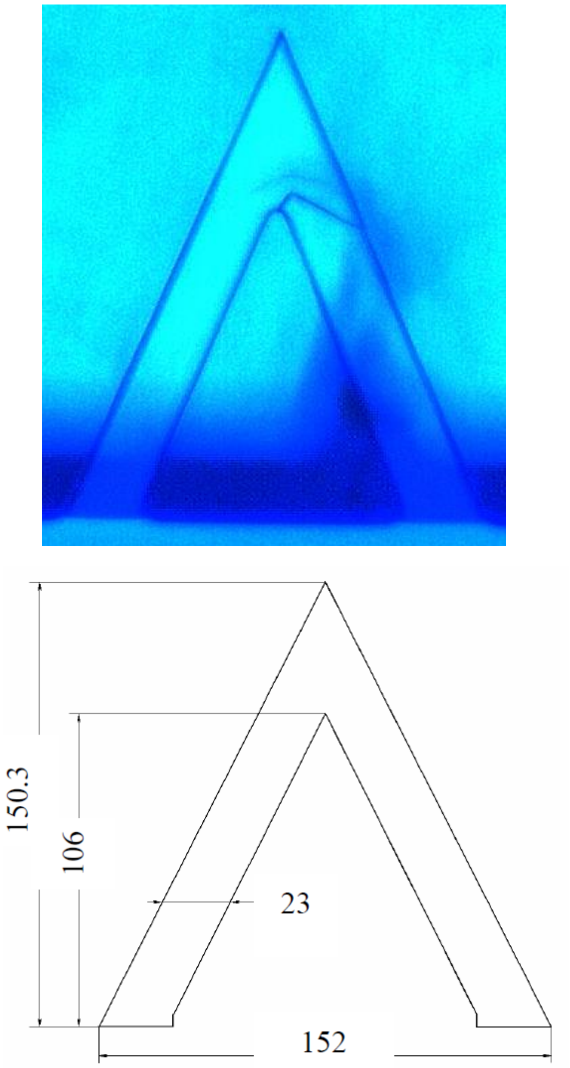

Fig -4: The cantilever beam of *triangular* shape after releasing from the silicon wafer – image on optical microscope. The dimensions from the sketch are given in μm. The structure thickness is SiO_2 layer thickness (1.7 μm)

3. STATIC CALCULATION OF THE MICRO-BEAMS

3.1 Trapezoidal Structure

A numerical computation using FEM with SolidWorks 2011/COSMOS M software has been performed. The calculation model is represented in Fig -5. The structure was considered as a mesh of 3334 elements of thin plate with 3 nodes per element (SHELL 3 model). 1863 nodes of interconnection have been resulted.

The micro-beam has been clamped at the base, and an uniformly distributed load, with the value of F = 1 μN, has been applied on the lateral surface of paddle.

To determine the spring constant of the micro-beam, the maximum deflection δ was established, using the formula:

$$k = F/\delta \quad [mN/m] \qquad (1)$$

According to Fig -6, a value of $\delta_{st} = |\delta_{st}|$ = 8.6 μm was obtained, resulting as value for the spring constant k = 116.2 mN/m.

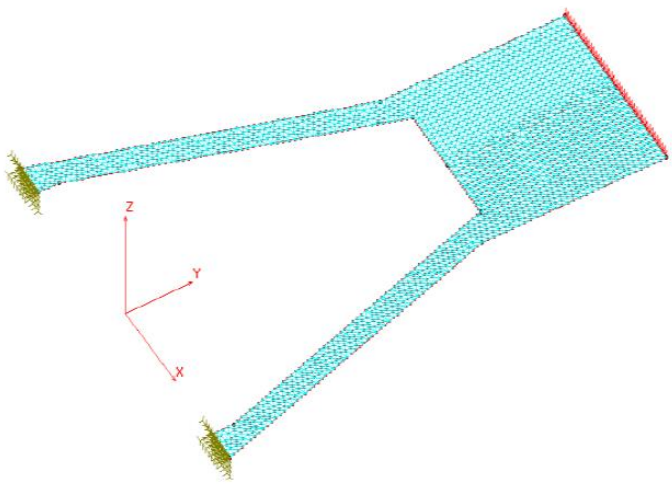

Fig -5: The calculation model for numerical simulation of cantilever beam of *trapezoidal* shape

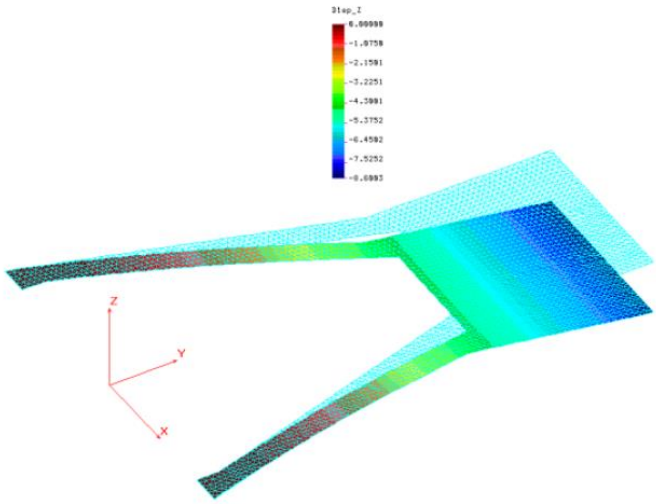

Fig -6: The static calculation of cantilever beam with *trapezoidal* shape

3.2 Triangular Structure

In a similar way with the previous structure, FEM method has been used. The structure was considered as a mesh of 3802 elements of thin plate with 3 nodes per element (SHELL 3 model). 2037 nodes of interconnection have been resulted. The calculation model is represented in Fig -7.

The micro-beam has been clamped at the base, and an uniformly distributed load, with the value of F = 1 μN, has been applied on a small surface from the tip of cantilever beam.

According to Fig -8, a value of $\delta_{st} = |\delta_{st}|$ = 0.7231 μm was obtained, resulting as value for the spring constant k = 1381 mN/m.

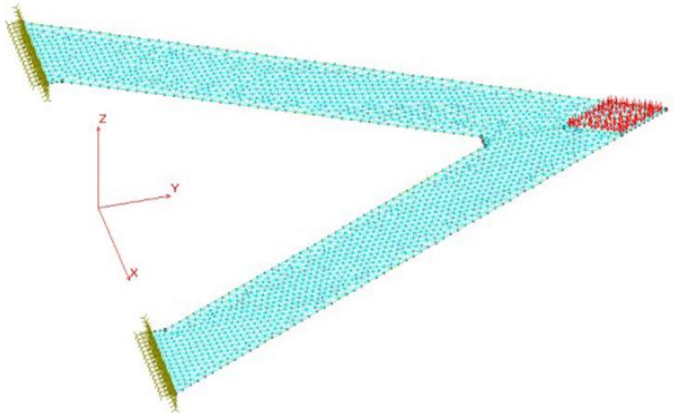

Fig -7: The calculation model for numerical simulation of cantilever beam of *triangular* shape

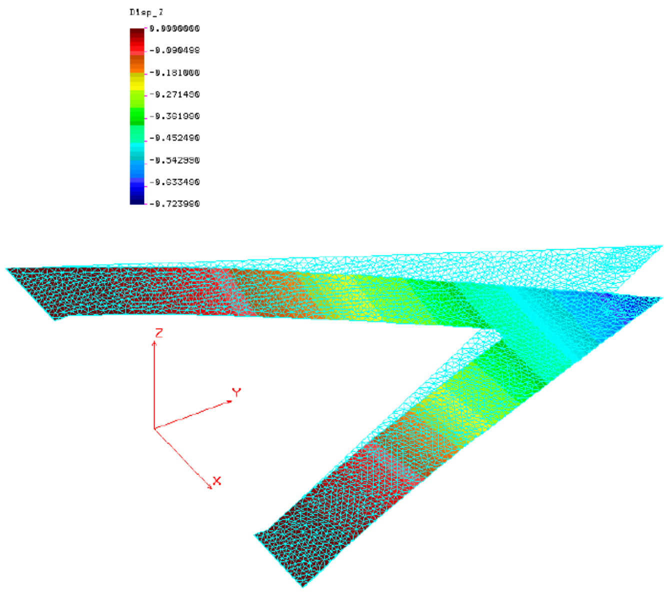

Fig -8: The static calculation of cantilever beam with *triangular* shape

4. DYNAMIC CALCULATION OF THE MICRO-BEAMS AND RESULT VALIDATION

Using the same calculation models, a dynamic computation has been performed, in order to determine the first (fundamental) eigen frequency and the first vibration mode [4]. The obtained results are presented in Fig -9 for the trapezoidal beam, and in Fig -10 for the triangular one.

In order to validate the dynamic calculation of studied structures, the MSA-500 Micro System Analyzer (Polytech), Fig -11, was used. It has a unique combination of non-contact measurement techniques: Scanning Laser-Doppler Vibrometry for characterization of out-of-plane vibrations, used by us in this research; Stroboscopic Video Microscopy for measurement of in plane motion and vibration; White Light Interferometry (WLI) for determination of surface topography; Geometry Scan data acquisition for the vibration measurement.

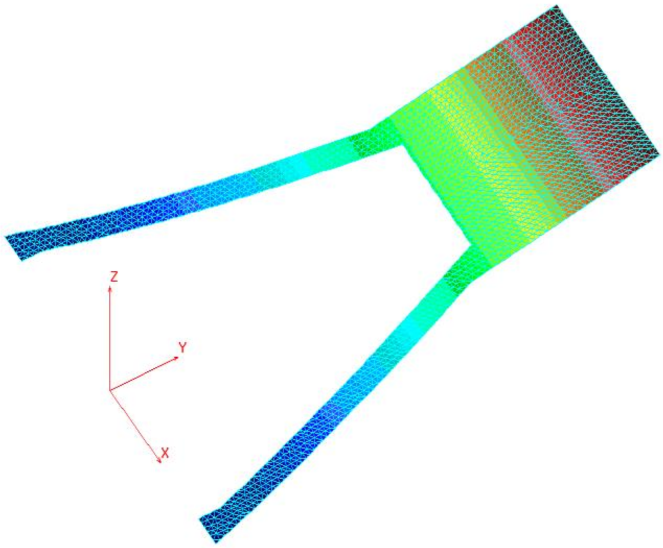

Fig -9: The dynamic calculation of cantilever beam with *trapezoidal* shape, F_Mode 1 = 20 150,6 Hz

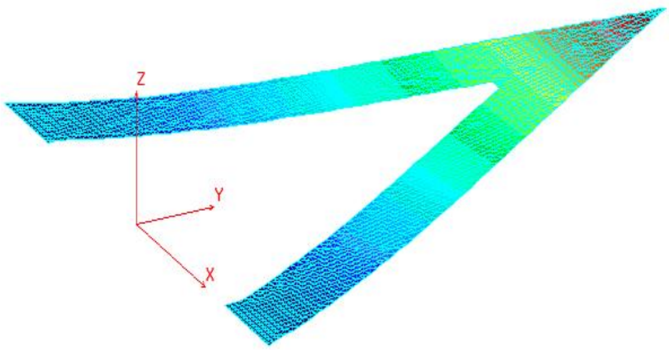

Fig -10: The dynamic calculation of cantilever beam with *triangular* shape, F_Mode 1 = 84 749,8 Hz

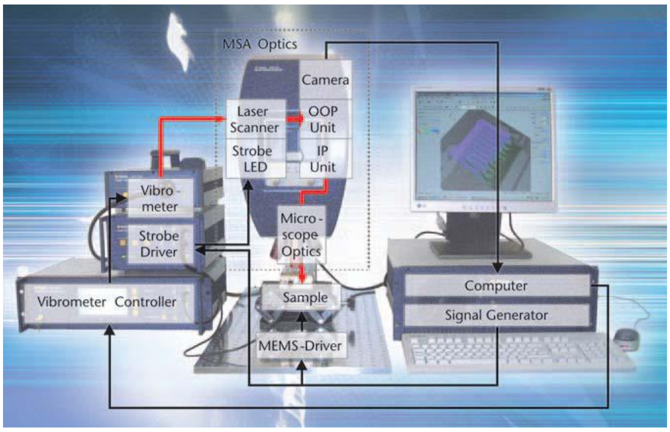

Fig -11: Schematic representation of the MSA

In Table -2, are given the results obtained through both numerical computation and experimental testing. A good agreement was obtained between experimental and computed frequencies: a relative error of ~ 2% for the triangular cantilever and of ~ 10% for the trapezoidal one.

Table -2: Resonant frequency values, numerically (FEM) and experimentally (LDV) determined

Structure type	Resonant frequency f_i, kHz	FEM method	LDV method
trapezoidal	f_1	20.15	22.50
triangular	f_1	84.75	83,13

5. CONCLUSIONS

In this paper, modeling, static and dynamic simulation, and an experimental validation of two MEMS structures are presented. The numerical computation model has been applied successfully for cantilever beams with complex geometries (triangular and trapezoidal shapes).

For a high value of spring constant and a low static deflection, a high resonant frequency results (the structure is rigid), which was demonstrated numerically and validated experimentally in case of triangular micro-beams.

On the contrary, for a low spring constant and a high static deflection, the resonant frequency decreases, as is the case of trapezoidal micro-beams.

In future research, the geometry optimization of these structures will be studied by changing the geometrical parameters depending on the desired application.

ACKNOWLEDGEMENT

This research was financially supported by the National Authority for Scientific Research (ANCS).

REFERENCES

[1] N. Lobontiu and E. Garcia, Mechanics of Microelectromechanical Systems, New York, Kluwer, 2005.

[2] G. Ionascu, Technologies of Microtechnics for MEMS (in Romanian), Cartea Universitara, Bucharest, Romania. 2004.

[3] G. Ionascu, L. Bogatu, A. Sandu, E. Manea and I. Cernica, "Modeling, Simulation and Technology of Microbeam Structures for Microsensor Applications", The Scientific Bulletin of POLITEHNICA University of Bucharest, Series D, Vol. 70, No. 3, pp. 19-30, 2008.

[4] G. Ionascu, A. Sandu, E. Manea, R. Gavrila, C.D. Comeaga, L. Bogatu and D. Besnea, "Influence of geometry and material properties on resonant frequencies and sensitivity of MEMS cantilever-type structures", J OPTOELECTRON ADV M, vol. 16, no. 5-6, pp. 579-590, 2014.