Aspects Regarding the Elastic Properties of Silicon and Its Influence on the Behavior of Micro-Mechanical Components

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Abstract - *A numerical simulation using Finite Element Method (FEM) of the behavior of micro-beams from MEMS sensors is presented in this paper, in order to determine the natural frequencies and the vibration eigen modes. Multiple possibilities of modeling the elastic properties of silicon, the material from which the micro-beams are made, have been considered. The obtained results are compared with analytical values, using relationships of the Vibration Theory, and also with values experimentally determined. Influence of silicon Young's modulus, estimated based on literature data and measured by nanoindentation, on resonant frequencies has been studied. The orthotrop behavior of silicon for such applications is highlighted.*

Key Words: Elastic Modulus, Structural Orthotropy, Micro-beams, MEMS Sensors

1. INTRODUCTION

Micro-Electric-Mechanical Systems (MEMS) represent the integration between the mechanical elements such as sensors and actuators with electronic devices on the same silicon substrate, processed through microfabrication technologies.

In the MEMS sensor structure, are frequently found micro-cantilever beams, they being the simplest resonant sensing elements with applications, for example, in the Atomic Force Microscopy (AFM) field. Micro-cantilever [1] having a nano-sized tip vibrates and interacts with a surface due to the intermolecular forces.

The most commonly used material for making micro-beams in MEMS sensors is the silicon, an anisotropic material with different elastic properties depending on the crystalline directions and the manufacturing technology of the microstructure. That's why the numerical simulation of mechanical, static and dynamic, behaviour of these structures is difficult in terms of modeling the silicon elastic properties.

In this paper, a numerical simulation using FEM of the behaviour of micro-cantilever beams from MEMS sensors is performed to establish the natural frequencies and the vibration eigen modes of these micro-mechanical structures.

The silicon was modeled as an *isotropic* material with values of elastic Young's modulus corresponding to the crystalline directions Si [100], [010], [001] – the coordinate axes of the cubic elementary cell ($E_x = E_y = E_z$). The silicon was, also, modeled as an *orthotropic* material for Si [110], [$\bar{1}$10], [001], representing the crystalline directions in the plane of silicon wafer (parallel to the flat and perpendicular to the flat/ chamfer of alignment in the working devices) and, respectively, the perpendicular direction on the silicon wafer surface ($E_x = E_y \neq E_z$). Influence of silicon Young's modulus, estimated based on literature data and measured by nanoindentation, on resonant frequencies has been studied.

The obtained results have been compared with analytical values, using relationships of the Vibration Theory, and also with values experimentally determined through two methods, by Laser Doppler Vibrometry (LDV) on MSA-500 Micro System Analyzer (Polytec) and by AFM on Ntegra Scanning Probe Microscope (NT-MDT Co.).

2. MODELING OF SILICON AS AN ISOTROPIC MATERIAL

The elastic behaviour of silicon depends on the crystallographic orientation of structure and, because of this fact, the choice of the best value of elastic modulus for a certain application has major consequences on the obtained results. In specialty literature, the values of silicon Young's modulus vary between 130 - 188 GPa [2]. Some authors recommend Si (111) for MEMS applications, which has an elastic modulus of 169 GPa [3].

The considered structures [4] are presented in Fig -1. The micro-cantilevers are obtained through micromachining techniques [5] and are manufactured from monocrystalline silicon, a material widely used in MEMS devices, due to its excellent mechanical properties and batch fabrication, compatible with micro-electronic components at low costs.
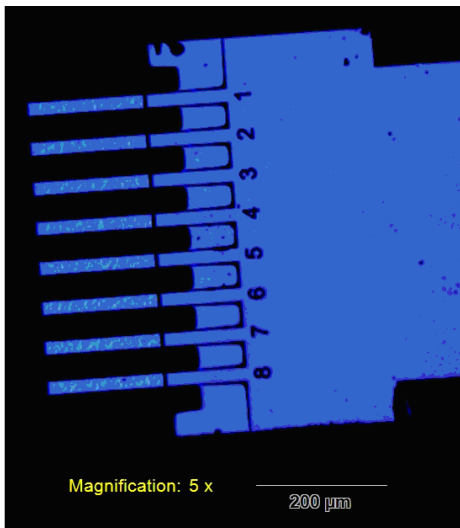

Fig -1: The studied microstructures (optical microscope image)

The microstructure under study in this paper has the geometry shown in Fig -2 and it is made from silicon with density ρ = 2330 kg/m³ and Poisson's ratio v = 0.22.

The micro-beam dimensions are length l = 727 μm (on the chip measured using a scanning electron microscope, also), width b = 90 μm and thickness t = 5 μm. For the Young's modulus, two values have been considered:
  a) E = 130 GPa, corresponding to Si (100);
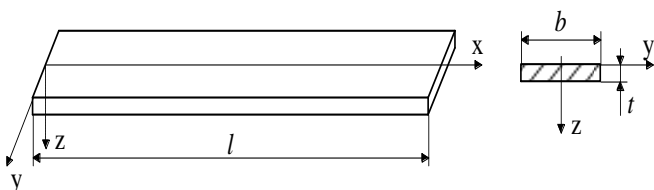 b) E = 169 GPa, corresponding to Si (111).

Fig -2: Sketch of the silicon micro-beam

2.1 Analytical Calculation of Natural Frequencies

For the bending modes, the resonance frequencies are computed with the following expression [6]:

$$f_i = \frac{n_i^2}{2\pi l^2}\sqrt{\frac{EI_y}{\rho A}} \tag{1}$$

where l is the length of the beam, E is the elastic modulus of the beam material, I_y is the inertia moment of the cross section related to y-axis; ρ is the density of material, A is the cross-sectional area of the beam, n_i are the coefficients with specified values corresponding to the vibration modes. Values of n_i are the followings: n_1 = 1.875, n_2 = 4.694, and n_3 = 7.855, corresponding to the first, second and the third vibration mode (bending). The torsion modes and the lateral one (in xy plane) have been analyzed only experimentally and through the finite element method (FEM), respectively.

2.2 Numerical Calculation of Natural Frequencies

A numerical simulation using FEM with SolidWorks 2011/COSMOS M software has been performed. The values of the first five natural frequencies and the corresponding vibration eigen modes have been determined. The calculation model is represented in Fig - 3. The structure was considered as a mesh of 4000 elements of thin plate with 4 nodes per element (SHELL 4 model). 4221 nodes of interconnection have been resulted.

The obtained results for the two values of the elastic modulus are presented in Table -1, comparatively with the analytical ones. A good concordance between the values of natural frequencies for bending modes is observed. Using FEM, the torsion vibration modes, and also, the ones in plane of micro-beam, can be identified. The calculation model is thus validated.
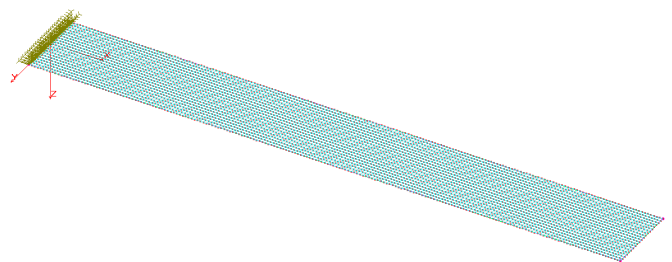

Fig -3: The calculation model for numerical simulation

Table -1: Resonant frequency values, determined by analytical and numerical calculation for isotropic model (E from literature data)

Resonant frequency f_i, kHz	Vibration Mode	E = 130 GPa		E = 169 GPa	
		Analytical method	FEM	Analytical method	FEM
f_1	bending	11.413	11.467	13.010	13.074
f_2	bending	71.533	71.83	81.559	81.900
f_3	torsion	-	187.48	-	213.760
f_4	bending	200.316	201.24	228.390	229.458
f_5	in-plane	-	203.31	-	231.810

3. EXPERIMENTAL STUDY
3.1 Experimental Determination of Natural Frequencies

The obtained results by analytical calculation and numerical simulation have been compared with those experimentally determined through two methods: LDV and AFM.

The Polytec MSA-500 system has been used to determine the natural frequencies by LDV method, respectively through out of plane vibration measurement of the cantilevers' surface [7]. The cantilevers chip is placed on a piezoelectric actuator, excited with a sinusoidal signal into frequency bandwidth starting from 1 Hz to 100 kHz, delivered by a function generator. Then, the user defines the scanning points and a laser beam is directed to the studied surface, following the previously defined grid. The vibration amplitude and frequency are determined using the Doppler shift of the reflected beam frequency due to the motion of the surface. The output of the laser-Doppler vibrometer is generally a continuous analog voltage that is directly proportional to the surface velocity component along the axis of the laser beam.

The experimental results are summarized in Table -2. By using this method, the in-plane vibration mode (the fifth vibration mode) cannot be observed. For the natural first mode fundamental frequency, the value of 13.28 KHz was determined.

This was validated through AFM method, employing the Ntegra Scanning Probe Microscope (NT-MDT Co.). The value of 13.4 KHz was determined, as an average value between two recorded values, 12.5 KHz and 14.3 KHz.

Table -2: Resonant frequency values, experimentally determined

Resonant frequency f_i, kHz	LDV method	AFM method
f_1	13.28	13.40
f_2	82.54	
f_3	202.70	
f_4	230.60	
f_5	-	

Comparing the numerical values with the experimental ones, it is observed that, at the first natural frequency, the error determined relative to the value measured by LDV is about 13.65% (for E = 130 GPa) and about 1.5% (for E = 169 GPa). Compared to the value measured by AFM, error is approximately 14.4% (for E = 130 GPa) and about 2.4% (for E = 169 GPa).

In conclusion, if an isotropic material model is adopted for silicon, the appropriate value for the elastic modulus is 169 GPa, corresponding to Si (111).

3.2 Measurement of Elastic Modulus by Nanoindentation

Indentation involves pressing an indenter into the surface of a sample. Depth and surface area of indentation are correlated with sample hardness. Berkovich indenter is the most commonly used for measurements of nanomechanical properties.

In order to validate the simulation results, it has been necessary to measure the Young's modulus of silicon cantilever. Nanoindentation, applied on the Nano Indenter G200 (Agilent Technologies) equipped with CSM (Continuous Stiffness Measurement) module, was used. Young's modulus is calculated from the slope of curve corresponding to the indenter withdrawing, the unloading curve being always in the elastic region.

The resulted value for the elastic modulus was E = 173.7 GPa, close to corresponding value for Si (111). The obtained values for the first five natural frequencies are given in Table -3 and they are very close to the experimentally determined ones.

Table -3: Resonant frequency values, determined by numerical calculation for isotropic model (E measured by nanoindentation) and orthotropic model

Resonant frequency f_i, kHz	Isotropic model (E measured by nanoindentation)	Orthotropic model (FEM)
f_1	13.255	13.019
f_2	83.039	81.580
f_3	216.710	184.051
f_4	232.270	228.410
f_5	235.010	230.922

4. MODELING OF SILICON AS AN ORTHOTROPIC MATERIAL

Because silicon is not an isotropic material, it was considered useful the numerical simulation for silicon as an orthotropic material, that is Si [110], [$\bar{1}10$], [001], representing the crystalline directions in the plane of silicon wafer (parallel to the flat and perpendicular to the flat/chamfer of alignment in the working devices) and, respectively, the perpendicular direction on the silicon wafer surface ($E_x = E_y \neq E_z$). The numerical values taken in calculation are: $E_x = E_y$ = 169 GPa; E_z = 130 GPa; ν_{yz} = 0.36; ν_{zx} = 0.28; ν_{xy} = 0.064; $G_{yz} = G_{zx}$ = 79.6 GPa; G_{xy} = 50.9 GPa. The results are presented in Table -3. In Fig -4 to Fig -7 are

shown the shapes of the first four vibration modes and the corresponding values of resonant frequencies, determined experimentally through LDV and calculated with FEM for orthotropic model.
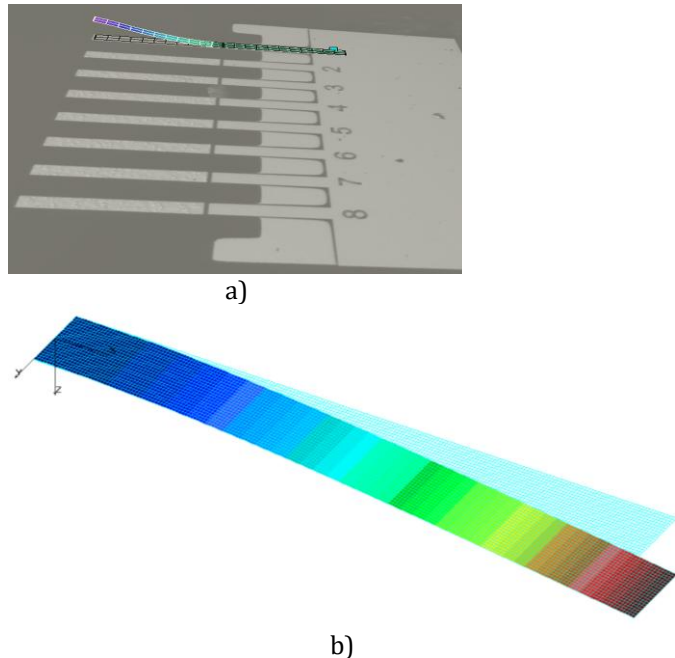

a)

b)

Fig -4: The first vibration mode – bending
a) experimentally through LDV (f_1 = 13.28 kHz)
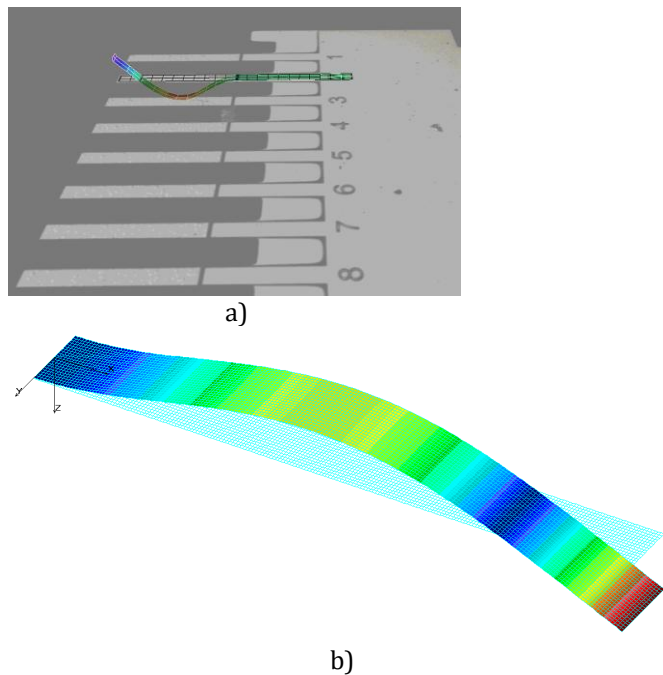b) calculated with FEM (F_Mode 1 = 13.019 kHz; error 1.96%)

a)

b)

Fig -5: The second vibration mode – bending
a) experimentally through LDV (f_2 = 82.54 kHz)
b) calculated with FEM (F_Mode 2 = 81.58 kHz; error 1.16%)
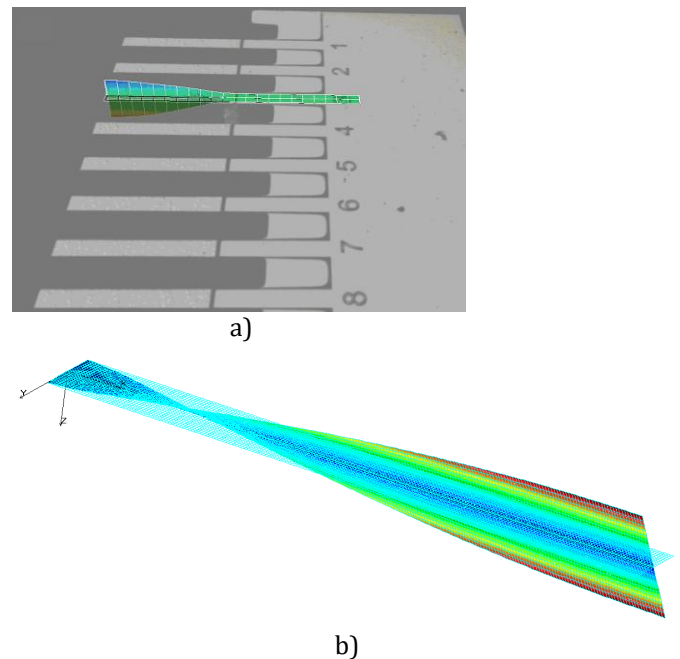

a)

b)

Fig -6: The third vibration mode - torsion
a) experimentally through LDV (f_3 = 202.7 kHz)
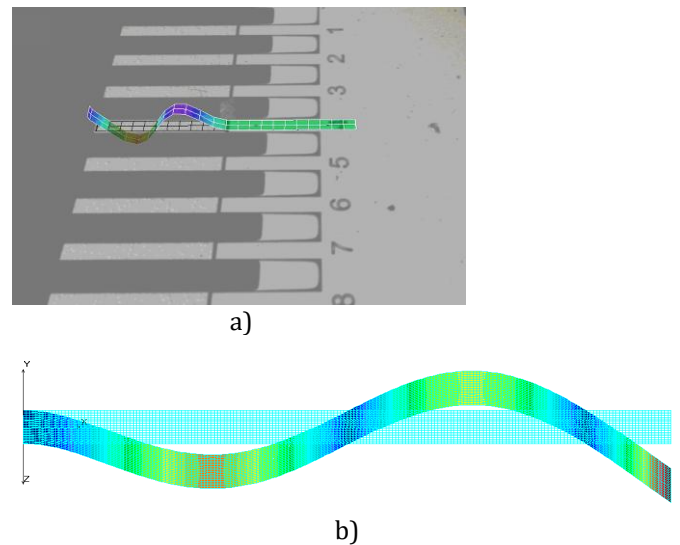b) calculated with FEM (F_Mode 3 =184.051 kHz; error 9.2%)

a)

b)

Fig -7: The fourth vibration mode - bending
a) experimentally through LDV (f_4 = 230.6 kHz)
b) calculated with FEM (F_Mode 4=228.41 kHz; error 0.95%)

5. CONCLUSIONS

In numerical simulations of the dynamic behavior of silicon microstructures under study, results experimentally confirmed are obtained in two ways of describing the elastic properties of the material:

1. isotropic material with elastic modulus $E_x = E_y = E_z =$ 169 GPa, the nearest value to the one measured

through nanoindentation (E = 173.7 GPa) on the actual structure;

2. orthotropic material with different values of the elastic properties, given in section 4.

It is noted that the obtained results for the natural frequencies are experimentally validated, errors being less than 3% in the case of the bending modes.

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