# Analysis of the Suspension Elements for the Sensitive Element of a Micromechanical Accelerometer

Ye Ko Ko Aung[1], Sergey P. Timoshenkov [2], Boris M. Simonov [3], Andrey C. Riabyshenkov[4]
Institute of nano and microelectronic
National Research University of Electronic Technology[123], Zelenograd, Moscow, Russia [123],
e-mail:1yekokoaung64675@gmail.com

*Abstract*— **Modern designs of sensitive elements of many MEMS, including micromechanical accelerometers, contain suspension elements, with the help of which the inertial mass is connected to a fixed frame. The simulation was carried out using the ANSYS program, the parameters and characteristics of the sensitive element of a micromechanical accelerometer with suspension elements of various designs made of silicon with different crystallographic orientations were investigated, and the values of their most important parameters were obtained. The natural frequencies of oscillations of the inertial mass, the residual mechanical stress in the structural elements of the sensitive element of the micromechanical accelerometer were calculated. Changes in the natural vibration frequency and residual mechanical stress in the suspension elements were determined when the temperature changed from +150 to –150 ° C in a short time interval (10 s). The change in the residual mechanical stress of the inertial mass of the sensitive element during impact was investigated. The results obtained made it possible to develop recommendations for choosing the design of a sensitive element with silicon suspension elements, which provide high sensitivity and stability of the parameters of a micromechanical accelerometer. The results obtained will be useful in the development of real designs of MEMS sensitive elements with optimal and stable parameters.**

***Keywords— MEMS - microelectromechanical system, micromechanical accelerometers, suspension, natural vibration frequency, residual mechanical stress.***

## I. INTRODUCTION

The micromechanical accelerometer is one of the most common MEMS devices due to their high demand for modern high-tech devices and devices that determine the level of scientific and technological progress [1, 2]. Currently, the use of capacitive sensors in industrial and consumer electronics is constantly growing due to a number of their significant advantages. First of all, one can note the high accuracy and reproducibility of measurement results, protection against overloads and strength, high efficiency (efficiency), small dimensions, and a wide range of operating temperatures. A schematic representation of the sensor is shown in Fig. one.

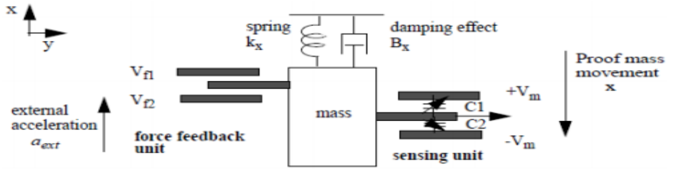


Fig. 1. Scheme of the capacitive acceleration sensor

Inside the sensor, there is a sensitive element, which has two rigidly fixed (stationary) plates and one central plate attached to inertial mass, which can be moved under the action of inertial forces due to elastic connection. At the same time, the distances between the movable and fixed plates change, which leads to changes in the capacities between the plates. Thus, this structure can be schematically represented as a series connection of two capacitors with equivalent capacitances C1 and C2. The capacity of one of them decreases, and the other increases by the expression:

$$C = \frac{A \times \varepsilon}{D} \tag{1}$$

where A is the area of the plate; ε is the relative dielectric constant of the medium between the plates; D is the distance between the plates.

Micromechanical accelerometer can be used both for measuring the projection of absolute linear acceleration on the coordinate axes and for indirect measurements of the projection of gravitational acceleration. Capacitive sensor’s parameters are used to solve a wide range of tasks - this type of device allows you to determine the position, movement, acceleration, and other parameters of an object's motion. Their application in automotive electronics is most often associated with accelerometers, which are most widely used due to their high sensitivity, stability in detecting static acceleration, low drift, and low-temperature sensitivity, and low power consumption, high reliability, good noise properties, satisfactory resolution, and accuracy, low price.

At present, different designs of micromechanical accelerometers have been developed and are used. Among them, the micromechanical capacitive accelerometers with comb drive construction have many advantages, such as high sensitivity and stability of the parameters of the capacitive accelerometer. Such micromechanical accelerometers can be used as a MEMS sensor; it can be designed with actuators (mechanical drives, actuators).

The stiffness coefficient of the suspension elements of the inertial mass of the sensitive element of the micromechanical accelerometer is determined by a combination of physical and geometric parameters of the suspensions, as well as the materials from which their structures are made; it affects the sensitivity and natural vibration frequency of the MMA [3].

In this article various suspension designs were studied. The first three modes of oscillation of the moving inertial mass of

978-1-6654-3941-1 @2021 IEEE

the sensitive element are especially important for equipment that uses a capacitive accelerometer. The first vibration modes are usually the working mode, the second and third are non-working modes, which should not have a parasitic effect on the operation of the MMA.

To ensure the stability of the operating parameters of the MMA, the natural vibration frequencies of the first, second, and third modes must be sufficiently different from each other. In this case, vibration in the direction of the working axis (X) of the first mode will not be affected by the second and third modes. The natural frequencies of the modes are influenced by the design parameters of the suspension elements.

When choosing the field of application of the capacitive micromechanical accelerometer, it is necessary to ensure the impact resistance of its structure [4], since micromechanical capacitive accelerometer can fail from impacts if the maximum permissible mechanical stress in them is exceeded [4]. There are many faults operation system take place in the accelerometers due to the following impacts, such as influences: sinusoidal and others, including random ones, vibrations, mechanical and thermal shocks, temperature fluctuations [5]. To ensure reliable operation and stability of the parameters of sensors, it is necessary to study the results of the influence of external factors at all stages of their life cycle.

The purpose of this work is to study the main types of suspension elements (suspensions) that are used in sensitive element of the type micromechanical capacitive accelerometer, as well as in other MEMS products.

## II. Analysis of Various Types of Suspension Beam Structure

The elements of the suspension of the inertial mass of the sensitive element can be elastic elements (springs) operating in torsion, bending, tension-compression. Folded springs are often used. Various types of suspension elements have been developed: straight beams, crab-leg beams, folded beams, serpentine beams, etc. [6].

The authors investigated three designs of suspension elements: folded beams with a rectangular cross-section (model 1), folded springs with a circular cross-section (model 2), and straight beams (model 3), during the calculations it was assumed that all suspension elements have identical geometric parameters. In the manufacture of MEMS devices and microsystem technology from monocrystalline silicon, it is possible to use silicon with the different crystallographic orientations of the surface - (100), (110), and (111). The following parameters of the investigated structures of suspension elements were chosen: width 35 µm; length 1065 microns; radius (for model 2) - 65 µrad. The area of the moving inertial mass is 500 µm x 1000 µm.

Calculations of structures of sensitive element of the micromechanical capacitive accelerometer with suspensions are performed. Using the well-known formula [7], for the inertial mass suspended on four springs, we write:

$$\left\{\begin{aligned} &\sum F_x = ma; \\ &-(k_1+k_2)x-(k_3+k_4)x = ma; \\ &ma+(k_1+k_2)x-(k_3+k_4)x = 0; \\ &ma+(k_{sum})x = 0; \end{aligned}\right\} \tag{2}$$

where $F_x$ is the force, $k_{sum}$ is the total stiffness coefficient of 4 folded springs, a is the acceleration, and x is the deformation of the sensitive element.

The resonant oscillation frequency f of an accelerometer with mass m can be determined from the equation.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{3}$$

where k is the stiffness coefficient of the suspension elements.

In [8] the coefficient of spring stiffness for folded beams was calculated. For a beam with a rectangular section:

$$\frac{1}{K} = \frac{1}{2}\left(\frac{L_1^3}{12EI}\right) + \frac{1}{2}\left(6(1+\mu)\times\frac{L_1}{5w_1tE}\right) + \frac{1}{4}\left(\frac{L_2}{ES_2}\right) - \frac{1}{4}\left(\frac{1}{4}\times\frac{L_1L_2^{\,2}}{EI_2}\right) \tag{4}$$

where K is the spring stiffness coefficient, $L_1$ and $w_1$ are the length and width of the first structural fragment, $L_2$ and $w_2$ are the length and width of the second structural fragment, $S_2 = L_2$ x $w_2$ is the area of the second structural fragment, $I_2$ is the moment of inertia of the second structural fragment.

In [8], the coefficient of stiffness of a folded spring with a circular section was calculated:

$$\frac{1}{K_c} = \frac{1}{Et}\left(\frac{L^3}{2w^3}\right) + \left(\frac{3(L+\mu)}{5w}\right)L + \left(\frac{24r^3}{wr^3}\right) - \left(\frac{\pi}{16} - \frac{1}{\pi} + \frac{1}{2\pi}\right) + \frac{3\pi L^2 r}{4wr^3} \tag{5}$$

where L is the length of the beam, w is the width of the beam, r is the radius of the section plane of the structural component, and µ is the Poisson's ratio.

The results of the investigated structures of inertial masses with suspension elements and the values of the calculated natural vibration frequencies of the sensitive element of the capacitive micro accelerometer, which is made of silicon 120 µm thickness with a surface orientation of (100) µm are shown in Fig 2.

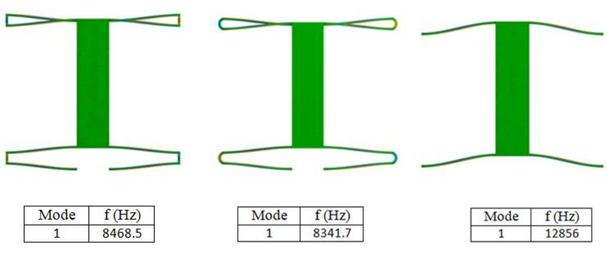


Fig. 2. The results of the natural frequencies of the sensitive elements of the model 1, 2 and 3

The natural frequencies of vibrations of sensitive element of the micromechanical capacitive accelerometer with suspension elements made of silicon with surface orientation (100), (110), (111) of different thickness, which varied from 40 to 120 μm, for the 1st, 2nd, and 3rd vibration modes were calculated in this article.

We found the following modeling results.

1. For the same orientation of silicon, the values of the resonant frequencies of the sensitive element oscillations with different thicknesses of the suspension elements differ.
2. For model 3, the values of resonant vibration frequencies for all suspension thicknesses are higher than for other models.
3. Models 1 and 2 have a low resonance frequency ratio of the second and first modes.
4. In model 3, the resonant vibration frequencies for the first and second modes are far enough from each other, therefore, vibration in the direction of the sensitivity axis X in the first mode will not be affected by the vibrations of the second and third modes [11].
5. The high values of the thickness of the suspensions can cause the high ratio of the resonant frequencies of the oscillations of different modes.

With silicon orientation (100), the model 3 is most suitable for working in high-precision MMA. Model 3 with a suspension element thickness of 120 μm has the greatest value of the ratio of the resonant frequencies of vibrations of different modes: 2.96 for a sensitive element made of silicon (100) and 3.00 for a sensitive element made of silicon (110). With silicon orientation (111), model 3 with a suspension element thickness of 120 μm has the highest resonant vibration frequencies of the studied modes 1-3 (15416, 46630, and 78387 Hz) and the ratio of resonant vibration frequencies of different modes is higher than in sensitive models made of silicon with the orientation ( 100) and (110).

Thus, when silicon with the (111) orientation is used, the suspension elements - straight beams with a thickness of 120 μm - are best suited for high-precision applications, providing the best instrument sensitivity and stability of its parameters.

## III. Residual Mechanical Stress in the Sensitive Element of the Capacitive Micromechanical Accelerometer

A study of the residual mechanical stress in the sensitive element of the capacitive micromechanical accelerometer with different designs suspensions during thermal shock was carried out. Residual mechanical stress is caused by several factors, including used materials, designs of parts and assemblies, manufacturing technology [9]. The reasons that cause it include temperature changes due to the difference in the coefficients of thermal expansion of the materials from which the sensitive element is made.

The ANSYS program was used to simulate the residual mechanical stress in the SE of various structures with elements of the suspension of the inertial mass of three models (Table 1). The effect of thermal shock on the magnitude and dynamics of changes in the residual mechanical stress in the elements of the SE structure has been studied. All the results were simulated by a rapid temperature change from +150 to –150 °C in 10 s).

I. RESIDUAL MECHANICAL STRESS IN THE SENSITIVE ELEMENT AT DIFFERENT TEMPERATURES

| **No. Model** | **Crystallographic orientation of silicon SE** | | | | | |
|---|---|---|---|---|---|---|
| | ***(100)*** | | ***(110)*** | | ***(111)*** | |
| | ***Suspension elements thickness, (μm)*** | | | | | |
| | ***40*** | ***120*** | ***40*** | ***120*** | ***40*** | ***120*** |
| 1 | 114.75 | 147.51 | 158.75 | 208.77 | 165.53 | 213.28 |
| 2 | 114.54 | 145.56 | 158.58 | 206.63 | 165.26 | 210.56 |
| 3 | 157.12 | 206.7 | 193.3 | 262.61 | 225.97 | 297.36 |

Figure 3 shows the results of modeling the residual mechanical stress in a sensitive element made of silicon with the orientation (100) with elements of the suspension of an inertial mass with a thickness of 40 μm for three models. The maximum residual mechanical stresses in the sensitive element at temperatures of +150 and –150°C correspond to the maximum deformations of the suspensions of the inertial mass. It is necessary to ensure that the residual stress is below the ultimate strength of silicon, equal to 440 MPa, so that the SE MMA can function properly.

It can be seen from the data in Table 1 that a significant factor influencing the residual mechanical stress in the elements of the SE MMA structure is the crystallographic orientation of silicon. The maximum residual mechanical stress occurs in model 3 with a suspension element thickness of 120 μm with a silicon orientation (111), and a minimum in model 1 with a suspension element thickness of 40 μm with a silicon orientation (100). With the orientation (100), the values of the residual mechanical stress in the sensitive element of the models 1 and 2 with the thickness of the suspension elements 40 μm are the smallest, which provides the highest MMA sensitivity. At the same time, it is obvious that the lower the residual mechanical stress in the MMA structures, the better the stability of its parameters and the higher the reliability. Therefore, when developing MMA with SE made of silicon, it is necessary to take into account these factors and find compromise solutions. The data obtained are useful in the development of MEMS devices with increased parameter stability.

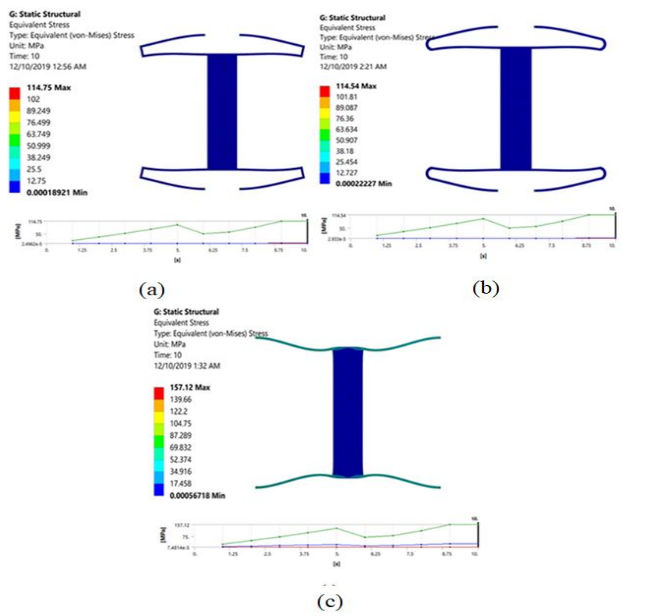


Fig. 3. Simulation results: residual mechanical stress in the sensitive element made of silicon with surface orientation (100) with elements of suspension of an inertial mass 40 µm thick of three structures of model 1, 2 and 3

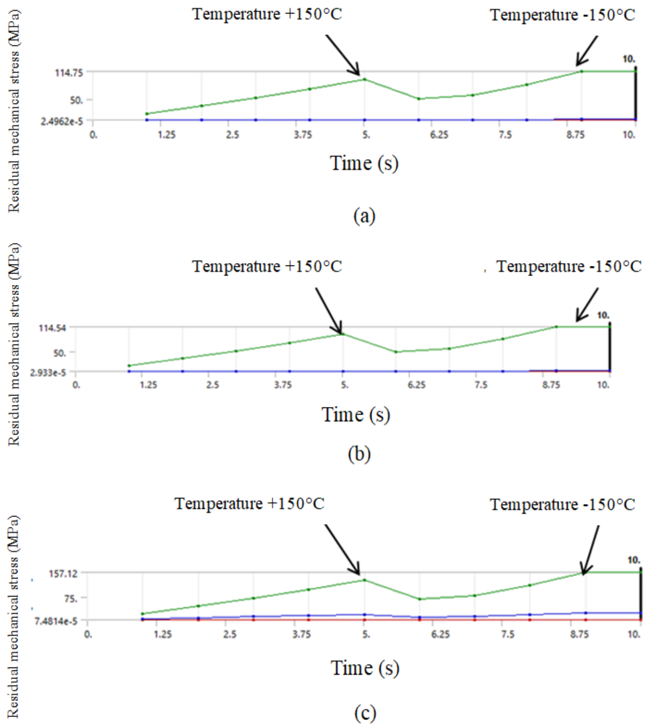


Fig. 4. Dependences of the mechanical stress of the sensitive element made of silicon with surface orientation (100) with elements of suspension of an inertial mass 40 µm thick of three structures of the model 1, 2 and 3

## IV. The Impact on the Suspension Elements of Inertial Mass

One of the most important conditions influencing the choice of the field of application and the commercialization of MEMS devices is their resistance to mechanical shock. MEMS can be subject to shock during manufacture, installation (deployment in operational conditions), and during operation. Mechanical shock can cause highly dynamic loads on structures and lead to cracking, chipping, and destruction of the product. In MEMS microstructures, in particular, suspensions can experience shock loads. Residual mechanical stress can arise in the suspension elements upon impact; its value depends on the thickness and crystallographic orientation of the surface of the structural material - silicon.

The impact on the suspension elements of the inertial mass is investigated. The results of calculating the mechanical stresses arising in the suspension elements under the shock action Ax, Ay, Az for models 1–3 at different orientations of the silicon surface are given in Table 2,3 and 4. From the Table 2, 3 and 4, the mechanical stress arising in the suspension elements upon impact depends on the thickness of the suspensions and the crystallographic orientation of the base material. If the impact occurs along the X-axis of sensitivity, then for this case the minimum mechanical stresses are obtained. The minimum stress is in model 3 with the orientation of the silicon surface (100) and the thickness of the suspension elements 120 µm. The minimum residual stress is characteristic for all investigated models with the orientation of the silicon surface (100).

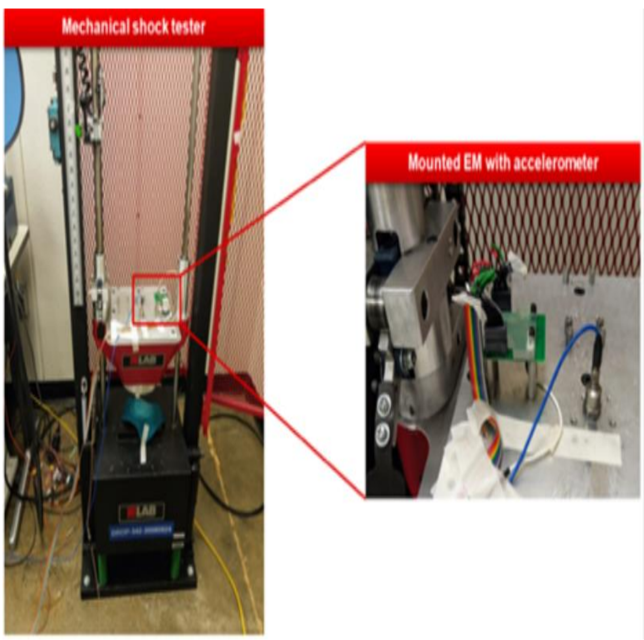


Fig. 5. High- g mechanical shock testing machine

II. RESULTS OF THE MECHANICAL STRESS IN THE SENSITIVE ELEMENTS UNDER SHOCK IMPACT CRYSTALLOGRAPHIC ORIENTATION OF SILICON (100)

| **Suspension elements thickness µm** | **External impact *A*, 10000 g** | | | **Mechanical stress on the folded beam , MPa** | | |
|---|---|---|---|---|---|---|
| | ***$A_X$*** | ***$A_Y$*** | ***$A_Z$*** | ***Model 1*** | ***Model 2*** | ***Model 3*** |
| **(100)** | | | | | | |
| 40 | + | – | – | 37.78 | 40.27 | 3.162,1 |
| | – | + | – | 290.7 | 277.7 | 256.44 |
| | – | – | + | 328.7 | 340.33 | 292.22 |
| 60 | + | – | – | 36.37 | 36.224 | 3.416,9 |
| | – | - | – | 255.22 | 250.43 | 259.23 |
| | – | – | + | 249.99 | 241.37 | 208.97 |
| 80 | + | – | – | 35.40 | 36.079 | 3.239 |
| | – | - | – | 246.03 | 250.18 | 237.03 |
| | – | – | + | 202.06 | 197.8 | 144.63 |
| 120 | + | – | – | 33.223 | 35.13 | 3.332,5 |
| | – | + | – | 232.76 | 245.69 | 225.21 |
| | – | – | + | 166.16 | 168.07 | 101.18 |

III. RESULTS OF THE MECHANICAL STRESS IN THE SENSITIVE ELEMENTS UNDER SHOCK IMPACT CRYSTALLOGRAPHIC ORIENTATION OF SILICON (110)

| **Suspension elements thickness µm** | **External impact *A*, 10000 g** | | | **Mechanical stress on the folded beam , MPa** | | |
|---|---|---|---|---|---|---|
| | ***$A_X$*** | ***$A_Y$*** | ***$A_Z$*** | ***Model 1*** | ***Model 2*** | ***Model 3*** |
| **(110)** | | | | | | |
| 40 | + | – | – | 44.6 | 46.94 | 3.420,3 |
| | – | + | – | 307.77 | 322.59 | 296.34 |
| | – | – | + | 344.81 | 356.74 | 313.46 |
| 60 | + | – | – | 44.22 | 43.825 | 3.637,2 |
| | – | - | – | 305.78 | 301.01 | 308.04 |
| | – | – | + | 237.22 | 253.95 | 224.39 |
| 80 | + | – | – | 44.07 | 44.581 | 3.457,9 |
| | – | - | – | 303.92 | 306.44 | 292.24 |
| | – | – | + | 213.14 | 209.34 | 156.5 |
| 120 | + | – | – | 42.939 | 44.846 | 3.494,5 |
| | – | + | – | 296.97 | 309.2 | 290.86 |
| | – | – | + | 174.86 | 176.43 | 168.4 |

IV. RESULTS OF THE MECHANICAL STRESS IN THE SENSITIVE ELEMENTS UNDER SHOCK IMPACT CRYSTALLOGRAPHIC ORIENTATION OF SILICON (111)

| **Suspension elements thickness µm** | **External impact *A*, 10000 g** | | | **Mechanical stress on the folded beam , MPa** | | |
|---|---|---|---|---|---|---|
| | ***$A_X$*** | ***$A_Y$*** | ***$A_Z$*** | ***Model 1*** | ***Model 2*** | ***Model 3*** |
| **(111)** | | | | | | |
| 40 | + | – | – | 38.314 | 40.184 | 3.181,6 |
| | – | + | – | 265.33 | 281.13 | 259.53 |
| | – | – | + | 330.29 | 341.8 | 293.93 |
| 60 | + | – | – | 37.316 | 36.82 | 3.432,9 |
| | – | - | – | 259.43 | 254.4 | 262.94 |
| | – | – | + | 251.08 | 242.55 | 210.24 |
| 80 | + | – | – | 36.073 | 36.73 | 3.255,9 |
| | – | - | – | 250.53 | 254.52 | 241.3 |
| | – | – | + | 203.15 | 198.77 | 145.62 |
| 120 | + | – | – | 33.919 | 35.815 | 3.494,5 |
| | – | + | – | 237.47 | 250.27 | 290.86 |
| | – | – | + | 167.4 | 168.66 | 109.19 |

The data obtained show that the mechanical stress arising in the suspension elements upon impact depends on the thickness of the suspensions and the crystallographic orientation of the material. The minimum stress occurs in model 3 when the silicon surface is oriented (100) and the suspension elements are 120 µm thick. If the impact occurs along the X-axis of sensitivity, then for this case the minimum mechanical stresses are obtained. The minimum residual stress is characteristic of all the models studied with the orientation of the silicon surface (100). Thus, model 3 is the best SE MMA, since this design option has the lowest residual stress. The greater the thickness of the suspension elements, that cause the lower the residual stress.

## V. CONCLUSIONS

A sensitive element (SE) made of silicon with the (111) orientation with suspension elements - straight beams (model 1) with a suspension element thickness of 120 µm has the highest resonant vibration frequencies of the studied modes (1–3) of the inertial mass and the ratio of resonant vibration frequencies of different modes in comparison with SEs made of silicon with surface orientation (100) and (110). Therefore, when using a sensitive element made of silicon with surface orientation (111) with suspension elements - straight beams with a thickness of 120 µm, they are best suited for high-precision applications, the stability of the MMA parameters is best ensured due to the maximum difference in the resonance frequencies of adjacent vibration modes.

For all the studied models, it was found that the thicker the suspension elements, the greater the value of the ratio of the resonant frequencies of oscillations of different modes and the higher the stability of its parameters.

All studied models have residual stress in the elements of the SE structure that is significantly lower than the strength of silicon, which is ~ 440 MPa. A significant factor influencing the residual mechanical stress in the elements of the sensitive element structure is the crystallographic orientation of silicon.

With a rapid temperature change from +150 to –150 ° C in 10 s, models 1 and 2 with a suspension element thickness of 40 microns have the lowest residual mechanical stresses (114.75 and 114.54 MPa, respectively) in a silicon cell with orientations (100). The maximum residual mechanical stress occurs in suspension elements with straight beams (model 3) with a suspension element thickness of 120 μm with silicon orientation (111), the minimum - in suspension elements - folded beams with a rectangular cross-section (model 1) with a suspension elements thickness of 40 μm with silicon orientation (100). With the orientation (100), the values of the residual mechanical stress in the sensitive element with suspension elements by folded beams with rectangular and circular cross-sections (models 1 and 2) with the thickness of the suspension elements 40 μm are the smallest, which ensures the highest MMA sensitivity.

Under the impact on the working axis X with amplitude of up to 10,000 g, the arising mechanical stresses in the elements of the suspension are the smallest in all the studied models when the silicon surface is oriented (100). CHE with suspension elements - straight beams in comparison with CHE with suspension elements - folded beams has the lowest outflow mechanical stress (3.3325 MPa) in structural elements.

## VI. References


[1] Hadi Tavakoli, Hadi Ghasemzadeh Momen, Edrahim Abbaspour Sani, “ Designing a New High Performance 3-Axis MEMS Capacitive Accelerometer “ 25th Iranian Conference on Electrical Engineering (lCEE) (May 2-4, 2017, Tehran, Iran), 2017, pp. 519-522.

[2] V.C. Jayanetti , W.A.D.M. Jayathilaka , K.I. Talawatta , Y.W.R. Amarasinghe, “ Design and Simulation of a MEMS Based Dual Axis Capacitive Accelerometer ” Moratuwa Engineering Research Conference (MERCon) (April 7-8, 2015, Moratuwa, Sri Lanka), 2015, pp.194-198.

[3] Hong Lianjin, Fang Erzheng, “Model Of Frequency Characteristics Of Capacitive Accelerometers,” IEEE International Conference on Measuring Technology and Mechatronics Automation (March 13-14, 2010, Changsha, China), 2010, pp. 668-670.

[4] Ion DIMA, Cristian-Gheorghe MOISEI, Calin-Dumitru COMAN, Mihaela NASTASE, Cristina-Diana LILICEANU, Alexandra Raluca PETRE, “Comparative study between random vibration and linear static analysis using Miles method for thruster brackets in space structures ” 5 th International Workshop on Numerical Modelling in Aerospace Sciences, NMAS (May 17-18, 2017, Bucharest, Romania), 2017, pp. 61-75.

[5] Karbari Sudha R, Kumari Uttara, Pasha Roshan C, Gowda Vikas K. “Design and analysis of serpentine based MEMS accelerometer,” AIP Conference Proceedings, 2017, vol-1966, pp.194-198.

[6] Avinash Kamble, Siddheshwar Khillare. “Comparative study of different flexures of MEMS accelerometers,”. International Journal of Engineering and Advanced Technology. 2015, vol. 4, pp. 22–25.

[7] Waichi W., Azid A.A., Mailis B.Y. “Formulation of stiffness constant and effective mass for a folded beam,” Archives of Mechanics, 2010, vol. 62(5), pp. 405–418.

[8] Wai Chi Wong, Ishak Abdul Azid, Burhanuddin Yeop Majlis. “Theoretical analysis of stiffness constant and effective mass for a round-folded beam in MEMS accelerometer,” Journal of Mechanical Engineering, 2011, vol. 57, pp. 517–525.

[9] Atsushi Kazama , Takanori Aono, Ryoji Okada “High Shock-Resistant Design for Wafer-LevelPackaged Three-Axis Accelerometer With Ring-Shaped Beam,” Journal of Microelectromechanical Systems, 2018, vol. 27, pp. 1-10.