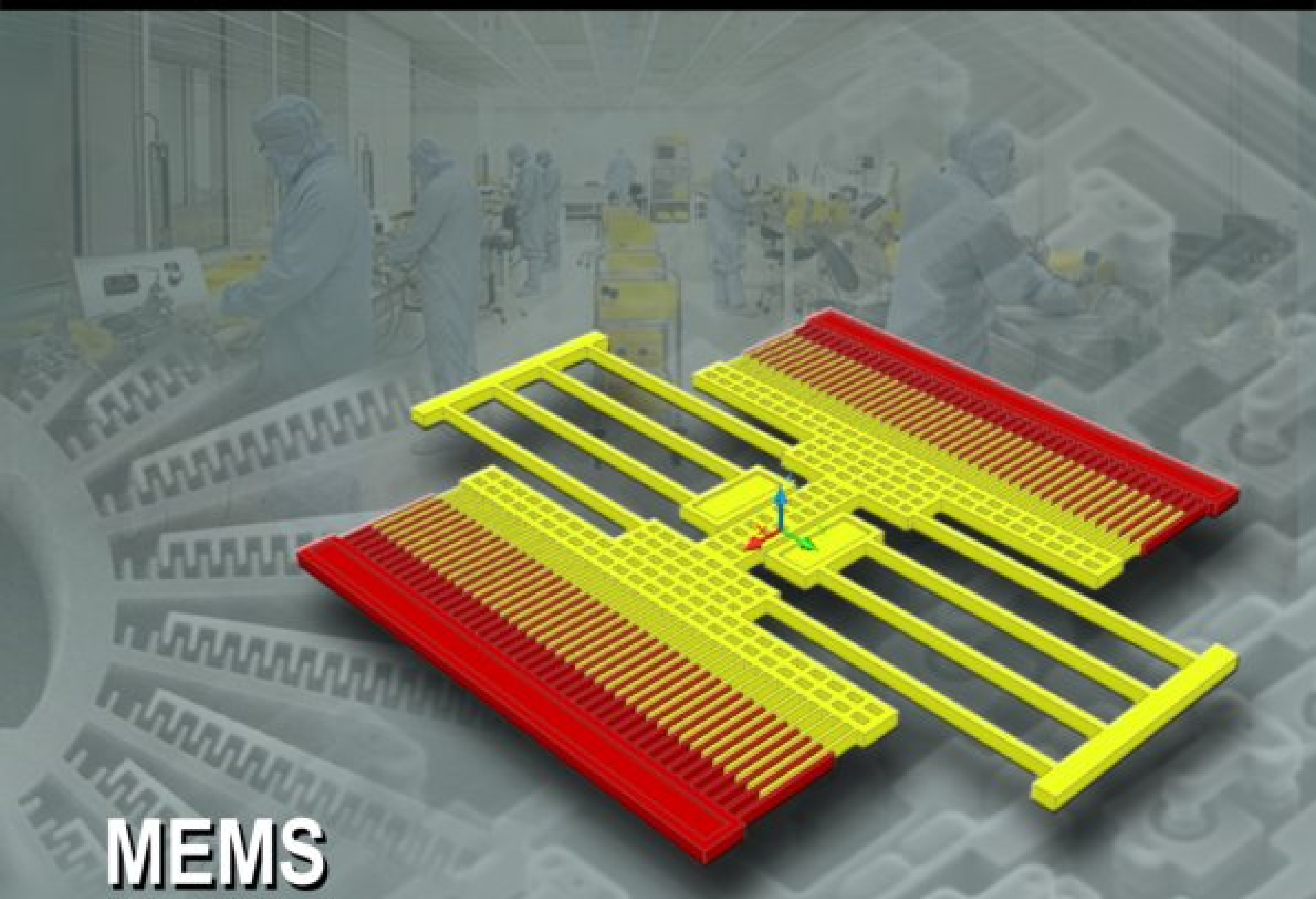
ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 103
4/09



MEMS and Modern Technologies

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 103, Issue 4
April 2009

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
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Sensors & Transducers Journal

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Volume 103
Issue 4
April 2009

www.sensorsportal.com

ISSN 1726-5479

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International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol. 103, Issue 4, April 2009, pp. 17-28

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Dual Comb Unit High-g Accelerometer Based on CMOS-MEMS Technology

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Received: 4 February 2008 /Accepted: 20 April 2009 /Published: 27 April 2009

Abstract: In this paper a capacitive based high-g accelerometer with superior level of sensitivity is presented. It takes advantage of dual comb unit configuration and surface micromachining fabrication process. All aspects of mechanical design such as sensor structure, modal analysis, energy dissipations, dynamic response and stresses in moving structure as well as anchors are described. Electrical circuit based on CMOS technology and its output signal is presented. Fabrication process and packaging are also discussed. The proposed sensor can endure impact loads up to 120,000 g (g = 9.81 m.s^{-2}) and achieves 16.75 µV.g^{-1} sensitivity with 5V bridge excitation voltage. Main resonant frequency of structure is found to be 42.4 kHz. Intended applications of suggested sensor include military and aerospace industries as well as field of impact engineering. *Copyright © 2009 IFSA.*

Keywords: High-g accelerometer, MEMS, Capacitive sensor

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1. Introduction

Micro-Electro-Mechanical-Systems technology, commonly known with the acronym MEMS, refers to the fabrication of devices with dimensions on the micrometer scale that contain both electrical and mechanical components. Accelerometers along with pressure sensors are the most commercially successful MEMS sensors with the largest market share [1]. They are mainly used in automotive industry for activation of safety systems (e.g. air bag) and control of vehicle stability. Further applications include measurement of mechanical shock, vibration and record of physical movements in medicine. They are also used in computers (protection of hard disk), robotics, seismology, cell phones (rotation of screen), navigation systems, medical devices, etc. [2-4].

High-g accelerometers which can withstand impact loads up to thousands of g are desirable for many commercial applications. They are applicable in test and measurement, aerospace, military (e.g. operational test and evaluation and smart munition guidance) and transportation industries. They are also used in impact, structural and transient shock testing [5-7].

Many high-g accelerometers rely on either piezoresistive or piezoelectric effect as transduction mechanism for their operation, although the later method is used less frequently. They are method of choice due to their simplicity and low cost fabrication. Furthermore both bulk and surface micromachining techniques can be applied for fabrication [8-12]. Capacitive interfaces on the other hand, have several attractive features. In most micromachining technologies no or minimal additional processing is needed. Capacitors can operate both as sensors and actuators. They have excellent sensitivity and the transduction mechanism is intrinsically insensitive to temperature. This sensing mechanism is independent of the base material and relies on the variation of capacitance when the geometry of a capacitor is changing.

In this paper, a surface micromachined capacitive sensor to measure high level of acceleration is presented. Proposed sensors showed very good level of sensitivity in comparison with its counterparts. Both finite element and analytical methods are used during the design process and evaluation of sensor performance. It is designed to be more reliable and sensitive than currently available sensors at relatively low cost in case of mass production.

2. Design

Dealing with high-g accelerations and demanding high sensitivity, led us to a structure much like a resonator in terms of geometrical shape as it contains two capacitive comb unit, flexure and truss beams, anchors and shuttle mass [13]. While resonators rely on electrostatic forces for their shuttle mass movement, in accelerometers this phenomenon is caused by external forces. Sensor layout and its components are shown in Fig. 1. Sensing mechanism is based on capacitance changes in two variable capacitors (comb units). When acceleration takes place, the shuttle mass moves and changes the capacitance of these two units oppositely. Change in capacitance is proportional to amount of acceleration and will be measured with integrated electrical circuit. Embedded etching holes reduce mass of structure as much as possible without sacrificing its robustness, beside their main role during fabrication process.

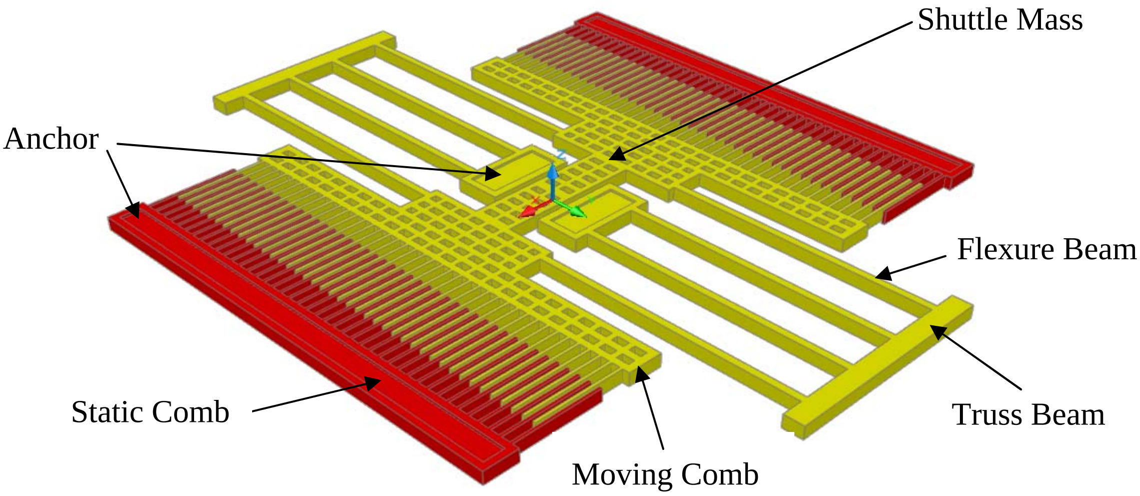

Fig. 1. 3D model of sensor structure and its components.

Important geometric dimensions of structure are listed in Table 1. Mechanical structure is designed to occupy minimal space as it measures 520 µm at its largest part. This leaves enough space for integrated electrical components on 1 mm^2 sensing chip. In static status, capacitance of each comb unit is more than 0.1 pF so variations can be measured by integrated circuit. Anchors are big enough to not only withstand applied stresses during vibration but ensure failure free operation for upcoming years considering hysteresis stresses, fatigue phenomenon and safety factors. Each comb unit consists of 41 fingers in moving comb and 42 fingers in static one. Structure flexibility allows displacements up to 20 µm between moving and static combs.

Table 1. Geometric Parameters.

Quantity	DIM (µm)	Quantity	DIM (µm)
Total length	520	Flexure beams length	194
Total width	434	Flexure beams width	5
Fingers length	65	Truss beams length	154
Fingers width	2	Truss beams width	14
Structure thickness	10	Central anchors length	54
Fingers side gap	2	Central anchors width	22
Initial length of overlaid fingers	45	Distance from substrate	2

3. Modeling

3.1. Natural Frequency

When acceleration acts on the mass of the structure, it produces a force on the flexure beams which deflects them causing mass displacement given by:

$$D = \frac{m.a}{k} \tag{1}$$

where D is the shuttle mass displacement, a is the applied acceleration, m and k are the effective mass and spring constant in desired direction (i.e. x, y, z). In addition to displacement, natural frequency of structure in x direction can be calculated as follows:

$$f_x = \frac{1}{2\pi}\sqrt{\frac{k_x}{m_x}}, \tag{2}$$

where k_x and m_x are the effective stiffness and mass in x direction. For structures similar to our configuration, effective spring constant in x direction is given by [14]:

$$k_x = \frac{2Etw_b^{3}}{L_b^{3}}\frac{L_t^{2} + 14\alpha L_t L_b + 36\alpha^2 L_b^{2}}{4L_t^{2} + 41\alpha L_t L_b + 36\alpha^2 L_b^{2}}, \tag{3}$$

where E is the Young’s modulus for structure material, t is the structure thickness, L_b and L_t are the length of flexure and truss beams, w_b and w_t are the width of flexure and truss beams respectively, α is the dimensionless parameter and defines as $(w_t / w_b)^3$.

Effective mass in x direction contains three components as follows:

$$m_x = m_{shuttle} + m_{t,eff} + m_{b,eff} \, , \tag{4}$$

where $m_{shuttle}$ is the mass of shuttle, $m_{t,eff}$ and $m_{b,eff}$ are the effective mass of truss beams and flexure beams respectively. Two last parameters can be calculated by following equations [14]:

$$m_{b,eff} = \frac{m_{beams}}{140} \frac{832L_t^4 + 16121\alpha L_t^3 L_b + 92706\alpha^2 L_t^2 L_b^2 + 138348\alpha^3 L_t L_b^3 + 62208\alpha^4 L_b^4}{(4L_t^2 + 41\alpha L_t L_b + 36\alpha^2 L_b^2)^2} \tag{5}$$

$$\begin{aligned} m_{t,eff} = \frac{m_{truss}}{280} (57L_t^6 + 1020\alpha L_t^5 L_b + 4644\alpha^2 L_t^4 L_b^2 + 1120L_t^4 L_b^2 + 17920\alpha L_t^3 L_b^3 + \\ 91840\alpha^2 L_t^2 L_b^4 + 161280\alpha^3 L_t L_b^5 + 90720\alpha^4 L_b^6) / [L_b^2 (4L_t^2 + 41\alpha L_t L_b + 36\alpha^2 L_b^2)^2] \end{aligned} \tag{6}$$

Effect of etching holes must be considered during calculation of truss and flexure beam masses. The natural frequency of structure in main direction (x axis) is found to be 40.06 kHz based on analytical analysis. This is approximately 5.6% lower than result obtained from FEA (finite element analysis) which discussed later. The difference can be justified with simplifications during formulation since the second approach offers more accurate results.

3.2. Capacitance

Basic operation of microsensor relies of comb fingers that form group of variable capacitors. For each capacitor formed of two parallel plates, capacitance is directly related to area of facing plates and inversely to distance between them. Some capacitive based sensors rely on horizontal movement between plates (i.e. change in distance) as their sensing mechanism. Our approach relies on vertical movement between static and moving comb fingers which changes area of facing plates. This method eliminates any chance of fingers deflection hence occurrence of short circuit as they encounter high level of accelerations. Capacitance model of each comb unit and parallel connection between capacitors are shown in Fig. 2. Each comb unit contains 41 fingers in moving comb and 42 fingers in static one. Total amount of capacitance for each comb unit and its components are listed in Table 2.

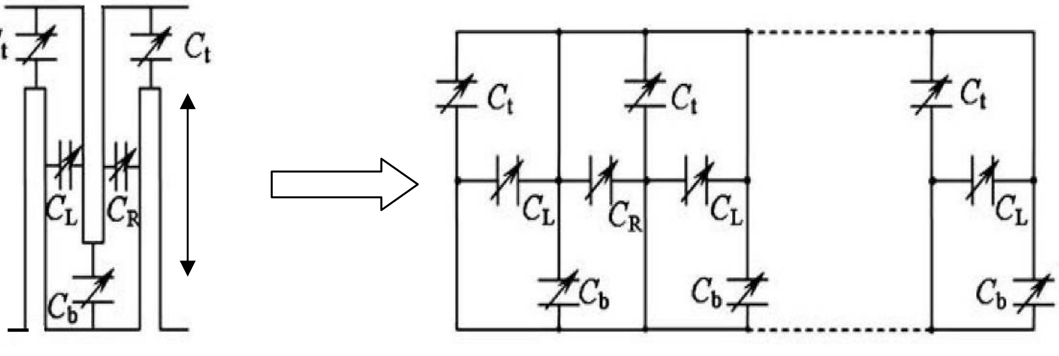

Fig. 2. Capacitance model of each comb unit and connection between its components.

3.3. Energy Dissipations

Energy loss phenomena in microdevices can generally be grouped into two large categories: One group contains loss mechanisms that are generated through intrinsic (material) dissipation, which also referred to as mechanical noise mechanisms [15]. The other group includes losses that are produced by fluid-structure interaction (i.e. slide film damping and squeeze film damping) [16]. Although material dissipations are subject of special importance in resonators, for structures that operate at much lower frequencies than their resonance (therefore have very low frequency ratio), these losses are so small and quite negligible [17]. Different types of energy losses by air viscosity that affect dynamic behavior of the structure are shown in Fig. 3.

Table 2. Capacity of each comb unit in stationary status.

Capacitor	**Capacity (pF)- Theory**	**Capacity (pF)- Simulation**
$C_t = C_b$	17.70*e*-6	18.78*e*-6
$C_L = C_R$	19.91*e*-4	21.12*e*-4
$C_{total} = 41*(C_R + C_L + C_t) + 42*C_b$	0.1647	0.1747

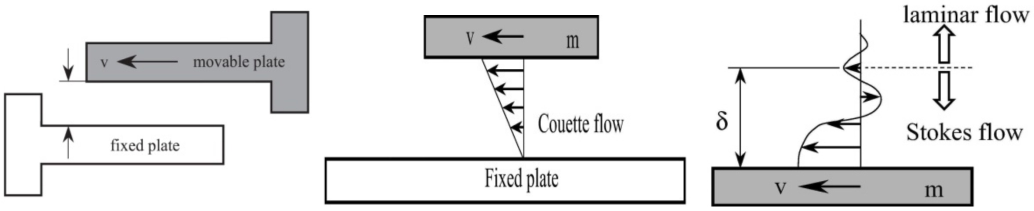

Fig. 3. Energy loss mechanisms imposed by air viscosity.

These losses include couette flow below the structure, Stokes flow above of it and flow of fluid between comb fingers. Analytical solution for calculation of fluid viscous damping in x direction is given by [18]:

$$c_x = \mu[(A_s + 0.5A_t + 0.5A_b)(\frac{1}{d} + \frac{1}{\delta}) + \frac{A_c}{s}], \tag{7}$$

where A_s, A_t, A_b, A_c are the area of shuttle mass, truss beams, flexure beams, side walls of comb fingers respectively. It has been suggested that for calculating the viscous damping force, small cross-section elements (e.g. comb fingers) should be weighted thrice as much as large plate masses to take into account edge and finite-size effects [18]. Other parameters are defined as follows: μ is fluid dynamic viscosity, d is distance between substrate and bottom of structure, δ is penetration depth of above fluid flow and s is side gap between comb fingers.

Since moving fluid above the structure is modeled by Stokes flow, its amplitude decreases logarithmically as it moves from the upper surface of structure. Penetration depth of fluid flow (δ) defines as “distance in which amplitude of fluid decreases by *e* factor” and relates to kinematic viscosity of fluid (v) and vibration frequency of structure (f). Plot of penetration depth for two fluids at 1 atmosphere and 25ºC as a function of frequency is shown in Fig. 4.

The mentioned parameter is given by following equation [18]:

$$\delta = \sqrt{\frac{2\upsilon}{\omega}} = \sqrt{\frac{\upsilon}{\pi . f}} \tag{8}$$

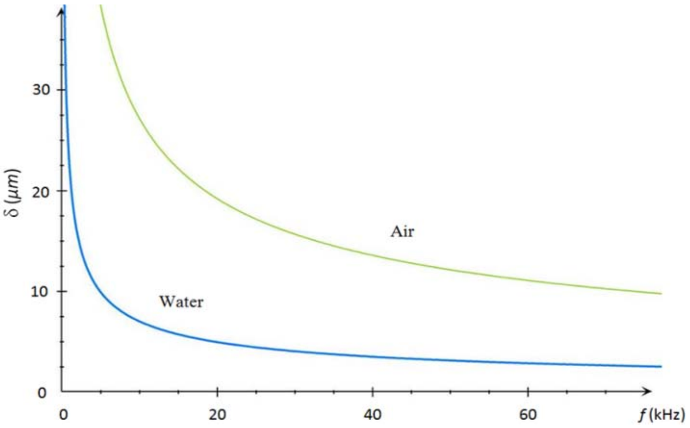

Fig. 4. Penetration depth vs. Frequency.

It can be concluded that effect of viscous damping becomes considerable only at high frequencies or in conjunction with relatively high viscous fluidics. For proposed sensor, calculated damping is 5.32 μN.S/m when it vibrates at 40 kHz in air medium. Therefore, presence of air as a viscous fluid almost has no effect in reducing response amplitude of system in comparison with ideally vacuumed environment.

4. Analysis

4.1. Modal Analysis

Analyze and simulation of structure is done using finite element analysis package. Its modal shapes and natural frequencies are extracted using modal analysis. Table 3 shows results of this analysis with total number of 8 modal shapes and their associated resonance frequencies within 0-200 kHz range. Natural frequency of structure is approximately 42.44 kHz in operating direction based on poly-silicon mechanical properties (E = 169 GPa, ρ = 2330 kg/m^3, υ = 0.22). Fig. 5 shows simulation results for first four modal shapes.

Table 3. Modal analysis results.

Mode Order	Resonant Frequency (kHz)	Mode Order	Resonant Frequency (kHz)
1	36.81	5	163.33
2	42.44	6	183.90
3	73.67	7	187.39
4	112.45	8	189.90

4.2. Stress analysis

Analysis of Von Mises and shear stresses in anchors are conducted to evaluate structure stability during operation. For this propose maximum displacement (20 μm) is applied to structure in its operating direction. Moving combs are removed during this process since their existence has no effect on final results and will only increase number of nodes/elements. Distribution of Von Misses stresses is shown in Fig. 6. Maximum amount being 590 MPa is roughly 0.35% of silicon Young's modulus.

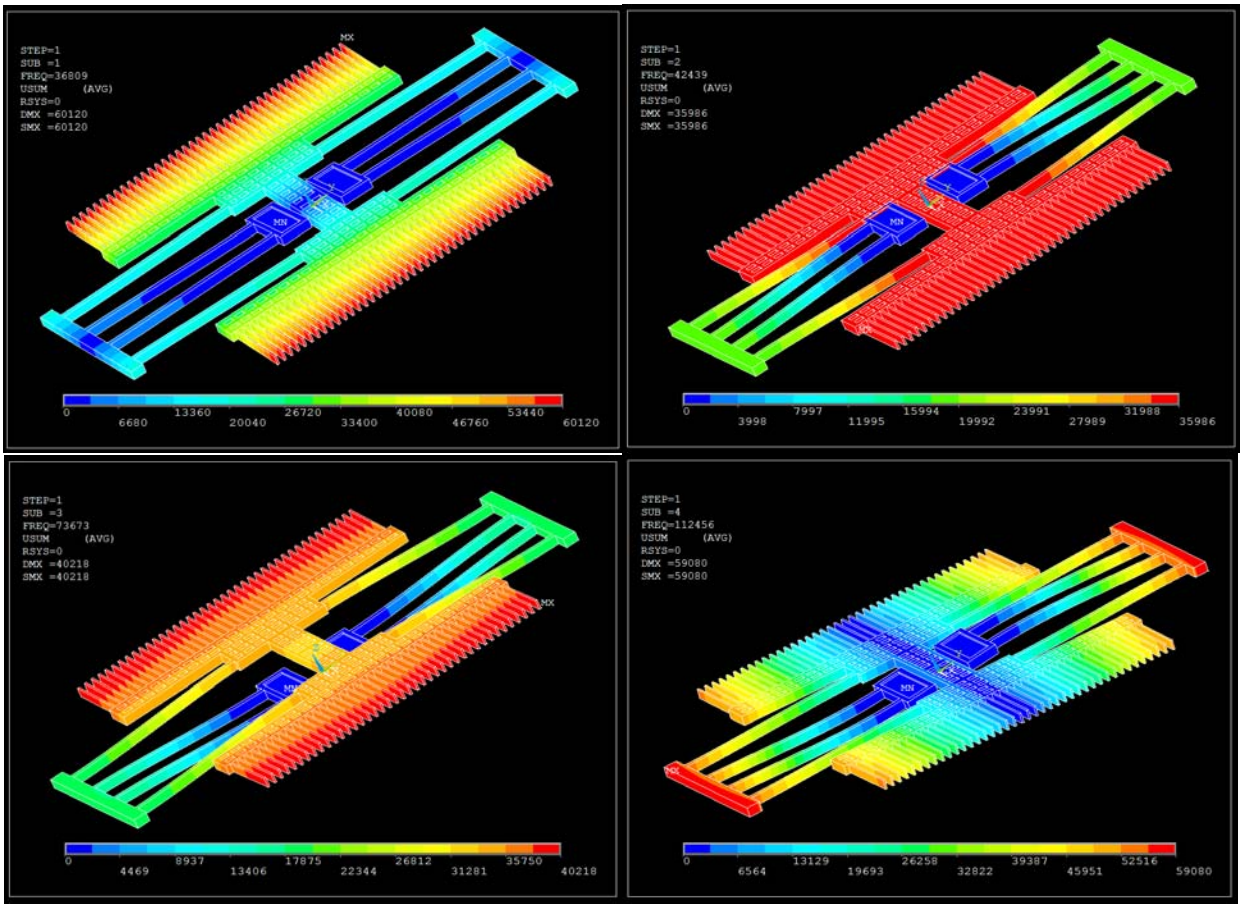

Fig. 5. Modal shapes for first four resonance frequencies of structure.

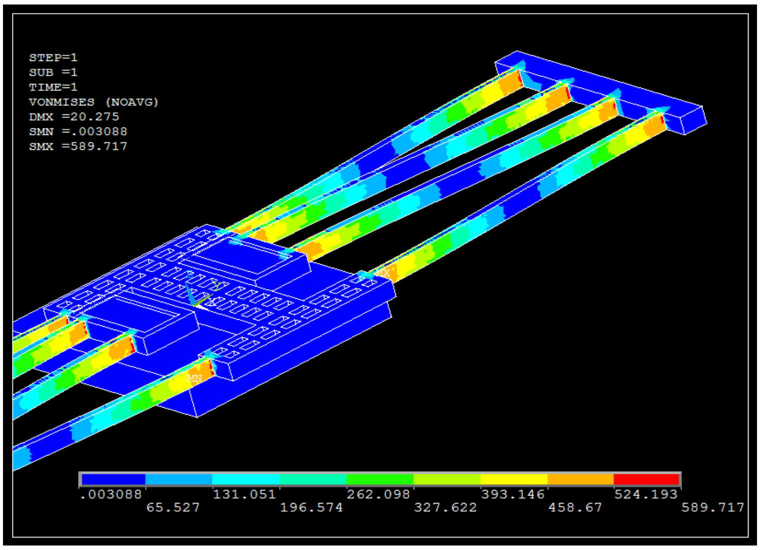

Fig. 6. Von Misses stresses in structure at max. displacement.

As shuttle mass moves forth and back, deflection at the end of each flexure beam, imposes a force at distance. This can be converted to its equivalent force and torque at anchors, which leads to formation of two shear stresses at each one. Stress intensity module is considered to evaluate their effect simultaneously and its distribution at anchors is shown in Fig. 7. Maximum amount (50 MPa) is much lower than anchors maximum stress threshold, because adhesion forces between poly silicon-silicon nitride-wafer layers are very strong.

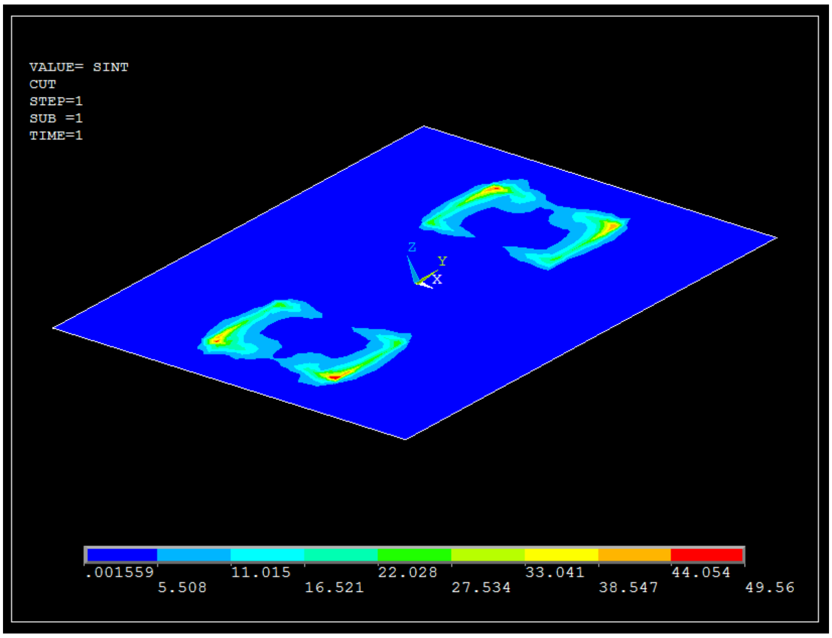

Fig. 7. Stress intensity in anchors attachment.

5. Electrical Components

Overall low capacitance of system requires integration of electronic capacitance measurement with signal conditioning circuit board on sensing chip. Integration of electronic components with mechanical parts is done with CMOS (Complementary Metal Oxide Semiconductor) technique. It offers many advantages over traditional discrete systems such as reduction in power consumption and space requirement, enhanced reliability and immunity to noise and distortion. Therefore microelectronics integration is subject of importance during development of modern sensors [19].

Fig. 8. shows a simplified view of accelerometer integrated electronic circuit for signal conditioning with I/O ports indicated with numbers. Input is first and second ports that are connected to two fixed comb anchors; third port is connected to anchors of moving comb and acts as output of sensor. The two capacitors are connected in series and form a capacitive divider. The two inputs into the device are driven differentially by a square wave generated by an oscillator with 2 MHz frequency. Bridge excitation voltage is 5V and amplitudes of the square waves on each capacitor are equal but with 180º phase difference.

In stationary status, the values of the capacitors are equal to each other and two signals cancel each other at the common summing node. Therefore output voltage to the amplifier which is mean value of square wave (DC voltage), equals to zero. During acceleration, capacitance of two comb units changes oppositely. This produces a signal at the summing node which is proportional to the amount of deflection. Ultimately, amount of acceleration is measured based on output signal.

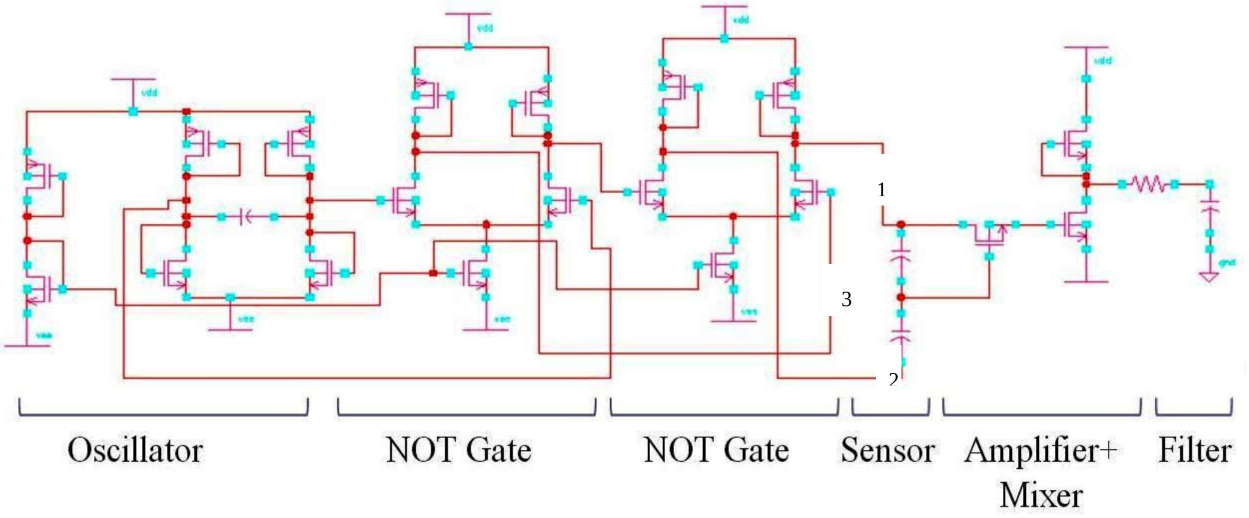

Fig. 8. Schematic view of sensor CMOS circuit.

6. Fabrication and Packaging

Designated fabrication process is standard surface micromachining with 1 μm pitch. Surface micromachined capacitive sensors have DC response and are inexpensive. They take advantage of fully established IC form factors for manufacturing process. This enables fabrication electrical measurement circuit on sensing chip which leads to a fully integrated system.

Major fabrication processes as shown in Fig. 9 include: Deposition of silicon oxide layer on Silicon wafer with 2 μm thickness then photolithography of deposited layer. This process is done with “Plasma Enhanced Chemical Vapor Deposition” (PEPCVD) technique. Wafer itself is coated with very thin layer of silicon nitride (a). Etching and structuring of silicon oxide layer and deposition of polysilicon layer with previous method (PECVD) and 10 μm thickness (b). Photolithography of deposited polysilicon and then etching and structuring of mentioned layer with “Deep Reactive Ion Etching” (DRIE) process. This process enables etching of silicon structures with very high aspect ratio and total 10 μm thickness of structure can be achieved with this method. Last step includes wet chemical etching of sacrificial layer (silicon oxide) with hydrofluoric acid (HF) which completes fabrication of structure. Embedded etching holes enhance removal process of silicon oxide layer during this process (d).

Packaging of the system begins with covering above of structure with Pyrex glass which along with substrate at the bottom restricts its vertical movements. Then all components are encapsulated and protected with resin. Further packaging procedures depends on sensor specific application and its location of installation. While selection of robust materials that could withstand imposed environmental tensions is essential for sensor proper functionality, it is demonstrated that its output voltage decreases slowly as Young's modulus or density of encapsulation resin increases [20].

Whole system including sensing chip and packaging, can fit in very small volume (e.g. 3 mm × 3 mm × 1 mm) based on mentioned parameters. Accelerometers unlike many other types of sensors such as pressure, chemical, etc. do not re1y on direct contact with sensing environment for their operation. This enables packaging to isolate the sensor completely from surroundings which ultimately enhances overall system’s durability and reliability.

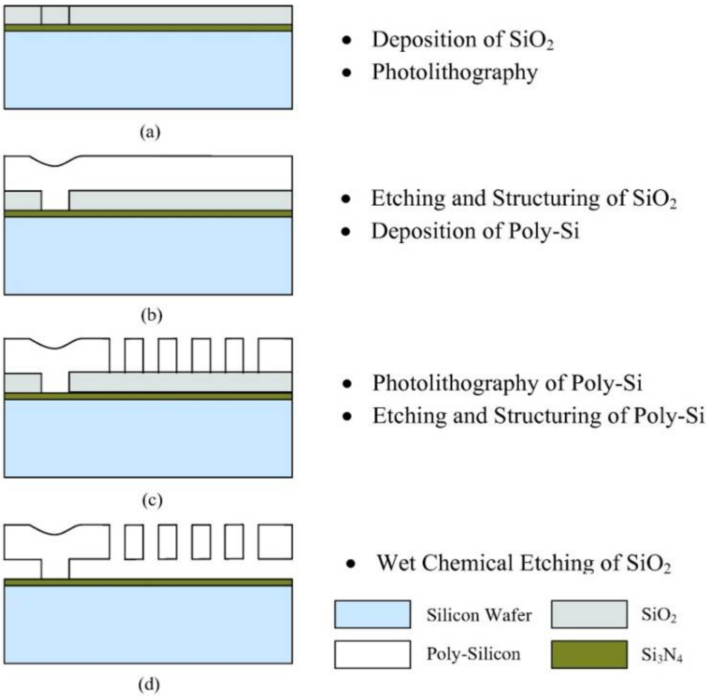

Fig. 9. Microstructure fabrication processes.

7. Response and Sensitivity

Sensor sensitivity along X-axis is modeled with coupling of electrical circuit equivalent to mechanical sensor with integrated electrical circuit. Corresponding values for shuttle mass displacement and two comb units (A, B) capacitance in correlation with acceleration, are listed in Table 4.

Table 4. Geometry and capacitance changes in correlation with acceleration.

Acceleration (×1000 g)	Displacement of Shuttle Mass (μm)	Unit A- (pf) Theory	Unit A- (pf) Simulation	Unit B-(pf) Theory	Unit B- (pf) Simulation
10	1.399	0.1691	0.1759	0.1588	0.1657
20	2.838	0.1760	0.1827	0.1539	0.1610
30	4.318	0.1816	0.1880	0.1483	0.1555
40	5.842	0.1854	0.1915	0.1425	0.1498
50	7.411	0.1912	0.1969	0.1369	0.1443
60	9.027	0.1973	0.2027	0.1309	0.1383
70	10.693	0.2036	0.2086	0.1249	0.1323
80	12.410	0.2102	0.2148	0.1187	0.1261
90	14.181	0.2172	0.2214	0.1122	0.1195
100	16.009	0.2250	0.2287	0.1058	0.1130
110	17.896	0.2349	0.2381	0.0987	0.1056
120	19.846	0.3332	0.3369	0.0918	0.0985

For calculation of capacitance, empty spaces at corner of two parallel plates are taken into account in simulation method; therefore their results show slightly higher values in comparison with theory. Plot of output voltage versus acceleration is shown in Fig. 10; comb units simulation values are considered to obtain final results (output voltages).

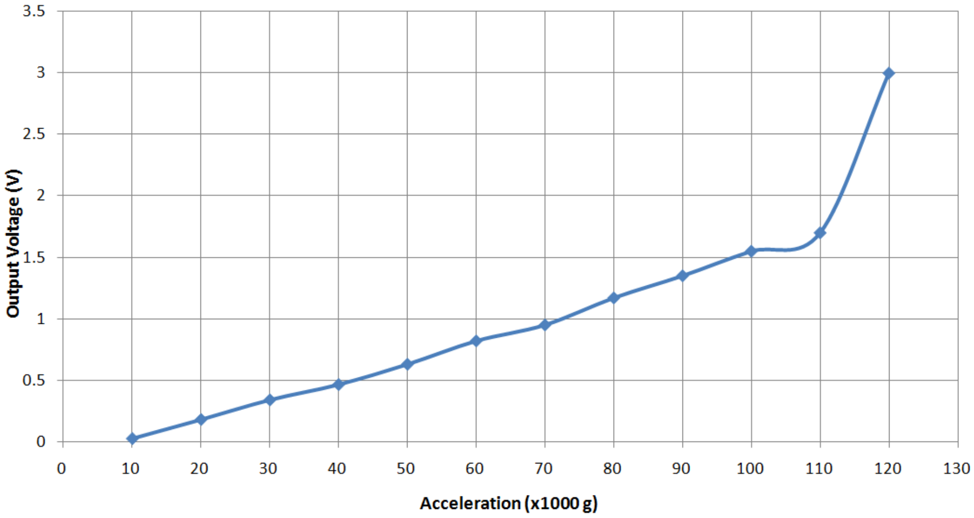

Fig. 10. Output voltage vs. Acceleration.

The results showed good linearity in 10-110 kilo-g range as shown in Fig. 10. Severe nonlinearity beyond 110 kilo-g, can be described by rapid growth of first unit's capacitance (A) between 110-120 kilo-g (41.8 % increase). Measured sensor sensitivity is found to be 16.75 $\mu V.g^{-1}$ in 10-110 kilo-g range. Comparison of proposed sensor with other five high-g accelerometers proves its very good performance among its counterparts; the results are shown in Table 5.

Table 5. Comparison with other accelerometers.

Sensor	Measurement Range (kilo-g)	Sensitivity ($\mu V.g^{-1}$)
Ref #8	2-200	1.43
Ref #9	Up to 13.7	3
Ref #10	Above 100	0.05-0.343
Ref #11	Up to 10	32
Ref #12	Up to 100	0.72
Proposed	10-110	16.75

8. Conclusion

Capacitive-based sensors have been used to sense pressure, force, acceleration, and flow rate. They are attractive for High Tech applications because the device performance is largely dependent on geometry deformation rather than base material properties. A CMOS-MEMS accelerometer for measurements up 110,000 g with exceptional level of sensitivity is demonstrated. This feature realized with capacitive sensing mechanism based on two comb units with large flexibility. Linear behavior and sensitivity of 16.75 μV/g observed over 10-110 kilo-g shock range. Due to its small size, high sensitivity and resistivity against shock, presented sensor has variety of applications in extreme impact sensing.

Acknowledgment

The authors would like to thank M. Baghelani for his helpful contribution throughout simulation and characterization of sensor.

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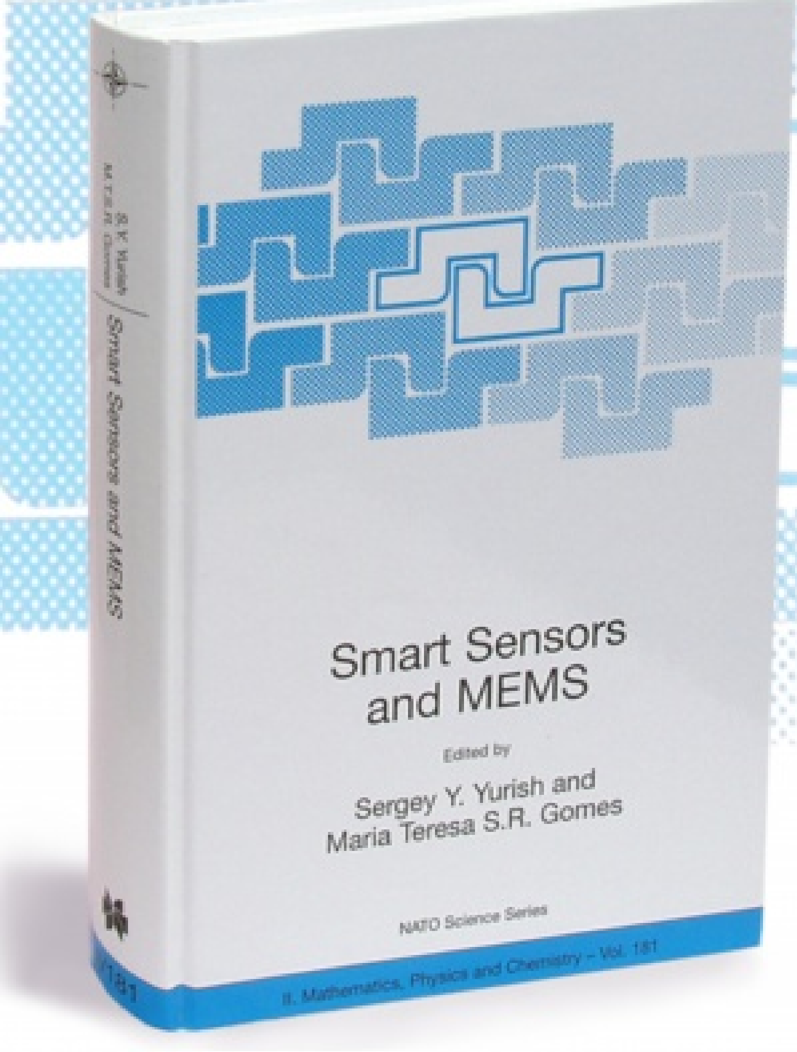
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