Design and simulation of Horizontal Accelerometers

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Abstract - **Microelectromechanical systems (MEMS) have the ability to reduce the size, weight, power consumption and cost (through batch fabrication/minimization of assembly and reduction in materials cost), while increasing reliability and performance of existing macroscopic devices. The MEMS-based inertial sensors have a wide range of applications in automotive, consumer, computer and navigation markets.**

This paper presents the design and simulation of four horizontal accelerometers, built on the same principles, with different geometry parameters. The main aim of the work is to investigate the displacement to x, fracture strength and capacitance of the sensors.

Keywords – **MEMS, Accelerometer, SoftMEMs and ANSYS CAD systems, PolyMUMPs**

I. INTRODUCTION

An accelerometer is internal sensor, used to measure acceleration. This MEMS-based accelerometer uses a capacitive-sensing scheme for acceleration detection. A simplified schematic of a capacitive accelerometer is shown in Figure 1 [1]. The central part of the accelerometer is a suspended mechanical proof mass, which acts as the sensing element. When the accelerometer is exposed to some acceleration, the proof mass moves relative to the substrate, subject to spring restoring forces and the damping, provided by the motion of air around the moving mass and comb fingers. The relative displacement is sensed by measuring the capacitance change between the comb fingers, as shown in the sensing unit in Figure 1. During the displacement sensing, modulation voltage V_m is applied across the sense fingers.

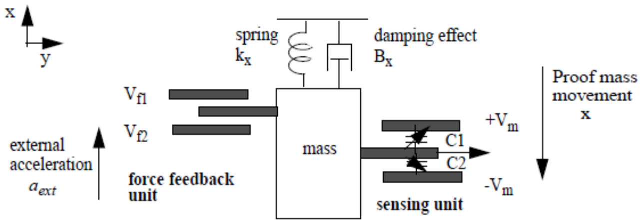

Figure 1. Schematic of a capacitive accelerometer.

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There are two basic techniques that are used to build MEMS – these are bulk and surface micromachining technologies. Latter is a fabrication technique, which builds mechanical elements by starting with a silicon wafer, and then etching away unwanted parts, and being left with useful mechanical devices. This is a relatively simple and inexpensive fabrication technology, and is well suited for applications, which do not require much complexity, and which are price sensitive. While Bulk Micromachining creates devices by etching into a wafer, Surface Micromachining builds devices up from the wafer layer-by-layer. In order to create moving, functioning machines, these layers are alternating thin films of a structural material and a sacrificial material. The structural material forms the mechanical elements, and the sacrificial material creates the gaps and spaces between the mechanical elements. At the end of the process, the sacrificial material is removed, and the structural elements are left free to move and function. Surface micromachining requires more fabrication steps than bulk micromachining, and hence is more expensive. It is able to create much more complicated devices, capable of sophisticated functionality.

II. ACCELEROMETER BASICS

Three-layer polysilicon surface micromachining process, called PolyMUMPs [2], is used for the fabrication of the accelerometers. It is one of the three Multi-User MEMS Processes (MUMPs®) that the company MEMSCAP is offering. MUMPs® is a well-established, commercial program that provides customers with cost-effective access to MEMS prototyping and a seamless transition into volume manufacturing and proof-of-concept fabrication to industry, universities, and government worldwide. Figure 2 is a cross section of the PolyMUMPs process. It has the general features of a standard surface micromachining process: polysilicon is used as the structural material, deposited oxide (PSG) is used as the sacrificial layer, and silicon nitride is used as electrical isolation between the polysilicon and the substrate.

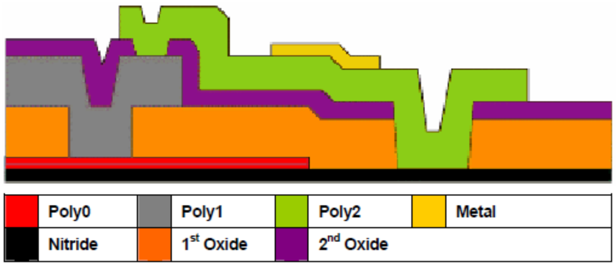

Figure 2. Cross section view, showing all 7 layers of the PolyMUMPs process.

Set of requirements and recommendations advisements that are defined by the limits of the process, which in turn is defined by the capabilities of the individual process steps, are called design rules. The purpose of that rules is to ensure the greatest possibility of successful fabrication. They have evolved through process development, the experience of the MEMSCAP staff, and most importantly, experience from previous runs.

The accelerometer consists of a movable proof-mass, suspended by two U-shape spring beams on both sides [3]. Movable comb fingers are attached to the proof mass. They are combined with the fixed comb fingers to form the sensing units. At two ends of the proof mass, there are four small rectangular cantilever beams, called limit stops. They are used to limit the displacement of the proof mass in the *x*- and *y*-directions, so that the comb fingers cannot touch together.

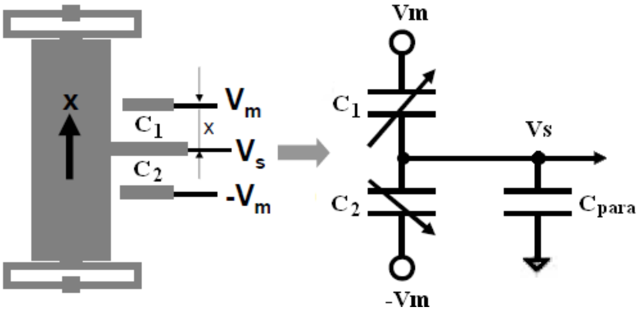

Figure 3. Equivalent schematic of capacitive accelerometer.

Simulations are made with SoftMEMs and ANSYS Multiphysics systems. The SoftMEMs CAD Design Environment is a customizable set of CAD tools for the development and test of MEMS-based products. SoftMEMs CAD tools are products that support leading electronic design automation environments, used for integrated circuit development. The applied tool suites enable designers to develop new MEMS designs and integrate existing designs into systems [6].

ANSYS Multiphysics is physics tool, combining structural, thermal, computational fluid dynamics, acoustic and electromagnetic simulation capabilities into a single software product. It is general purpose analysis tool, allowing engineers and designers to combine the effects of two or more different, yet interrelated physics, within one, unified simulation environment. Simulating the interaction between structural mechanics, heat transfer, fluid flow, acoustics and electromagnetic is possible [7].

III. DESIGN AND SIMULATION OF THE ACCELEROMETERS

The electrical circuit of the accelerometer from Cadence Virtuoso Schematic Editor is shown in Figure 4. It is composed from the cells of the tethers, proof-mass and sources for position. In order to evaluate the performance of the sells, we need a set of lumped-parameter models, to describe the device behavior as a function of the physical design variables. The models are written in Verilog A language and include the effective stiffness of the spring, the effective masses of the springs and the proof mass, viscous air damping, electrostatic force and the capacitive sensing interface. Analysis for displacement and capacitance of the electrodes C_1 and C_2 are made in Cadence Virtuoso Analog Design Environment.

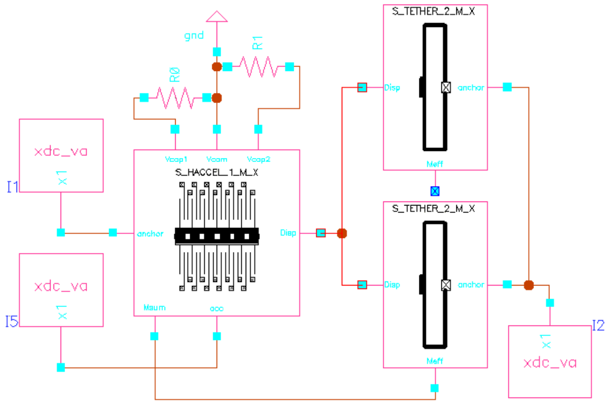

Figure 4. Electrical circuit of the accelerometer in Cadence Virtuoso Schematic Editor.

The results of the displacements when external acceleration occurs are shown in Figure 5. All of the structures are designed to have 1 μm displacement of the proof-mass, when the acceleration is equal to a_{MAX} (full range).

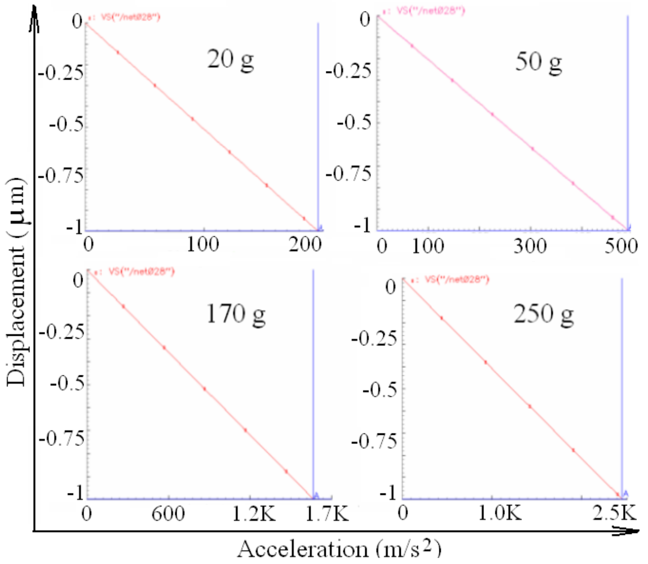

Figure 5. Analysis of displacement for sensors with full ranges of 20, 50, 170 and 250 g (m/s^2).

Diagrams from the disbalance of the capacitances C_1 and C_2 are shown in Figure 6.

Diagrams from the capacitances C_1 and C_2 are shown in Figure 7.

The layout of the capacitive accelerometer, used in our synthesis is shown in Figure 8. The topology is similar to the ADXL150 commercial accelerometer from Analog Devices. Parameters, used to specify the accelerometers performance are bounded by the functional constraints, listed in Table 1.

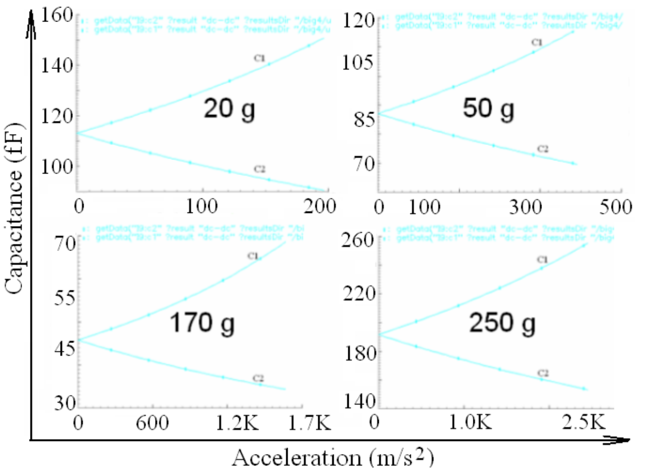

Figure 6. Results from analysis of capacitances disbalance against acceleration for all of the sensors.

After finishing analysis in SoftMEMS, we export the structures to ANSYS. There, we are defining the material property values of the polysilicon, meshing the models using the element SOILIDXX. In Figure 9 is shown analysis of displacement for one of the structures. The result from this analysis is 10% lower than the displacement, calculated by the Verilog A models, which can be explained with the difference between the methods, used from those softwares. The proof-mass, colored in yellow, have the biggest displacement in the sensor and moves at around 900 nm from the initial position.

TABLE 1. FUNCTIONAL CONSTRAINTS.

Parameter	**Acc. 1**	**Acc. 2**	**Acc. 3**	**Acc. 4**	**Unit**
Effective masse model [m_X]	$2,4.10^{-9}$	$1,02.10^{-9}$	$3,9.10^{-10}$	$1,2.10^{-9}$	kg
Mechanical spring stiffness [k_{mech}]	0,478	0,512	0,651	2,987	N/m
Electrostatic spring softening [k_e]	-0,014	-0,011	-0,01	-0,024	N/m
Effective spring constant [k_{eff}]	0,4643	0,501	0,641	2,963	N/m
Air damping model [B_X]	$4,6.10^{-6}$	$2,1.10^{-6}$	$0,9.10^{-6}$	$2,5.10^{-6}$	N/m^2
Resonant frequency [f_R]	2,231	3,528	6,495	7,901	kHz
Mechanical bandwidth [f_{3dB}]	3,455	5,474	10,087	12,273	kHz
Quality Factor [Q]	7,22	11,09	18,57	23,43	
Capacitance [C_0] (acceleration = 0g)	113,1	87,1	45,8	191,7	fF
Capacitance C_1 (a_{MAX})	150,8	116,1	68,8	255,3	fF
Capacitance C_2 (a_{MAX})	90,5	69,7	34,3	153,5	fF
Misbalance of the capacities (a_{MAX})	60,3	46,41	34,5	101,8	fF
Mechanical sensitivity [x/a]	50	20	5,88	4	nm/g
Sensitivity [(C_1-C_2)/g]	3014	928	203	407	aF/g
Area of the accelerometer [A]	1,24	0,78	0,586	1,25	mm^2

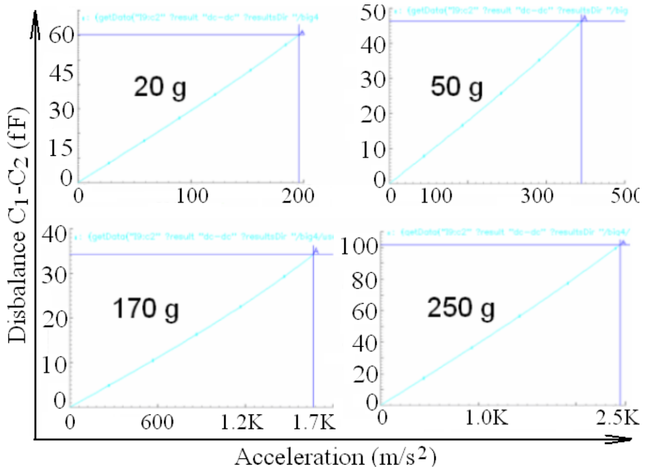

Figure 7. Acceleration against capacitance and diagram.

In Figure 10 is shown *von Mises* analysis, used to estimate yield failure criteria in ductile materials. The most critical points of the structure are these, which suffer the most and which are submitted to pressure of 7 MPa. They are painted in purple color. These values are far bellow the fracture strength of the polysilicon - 1GPa.

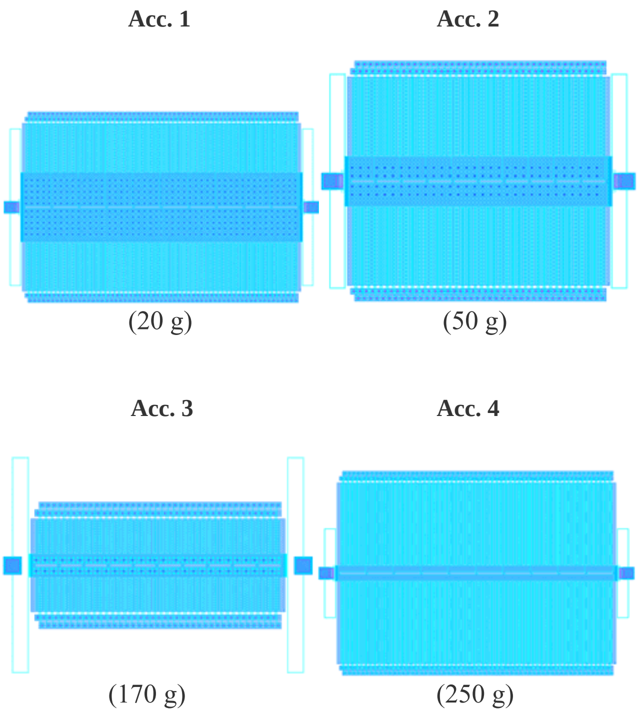
Acc. 1 (20 g)
Acc. 2 (50 g)
Acc. 3 (170 g)
Acc. 4 (250 g)

Figure 8. Layout of the accelerometers.

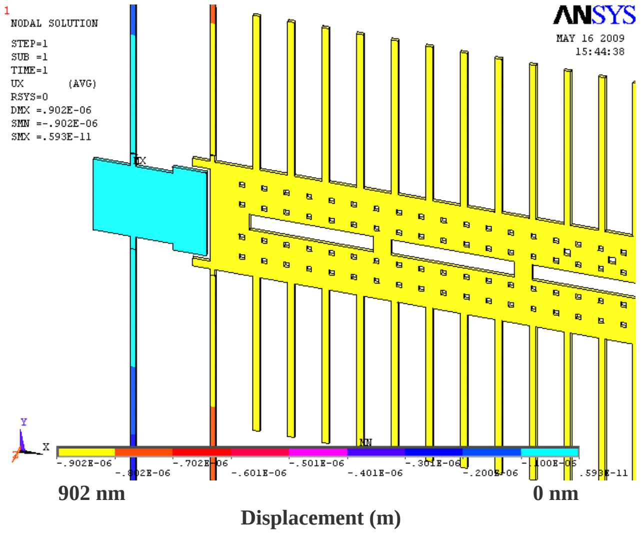

Figure 9. X-displacement analysis of an accelerometer in Ansys.

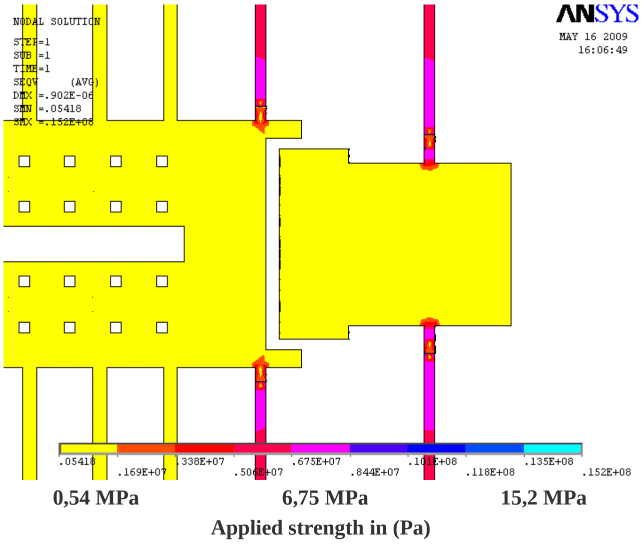

Figure 10. Analysis for fracture strength (*von Mises*) in Ansys

IV. CONCLUSION

This work demonstrates a design of capacitive horizontal accelerometers, which are used in automotive industry for airbag opening. The simulations are performed, using ANSYS and SoftMEMs CAD systems. A parametric coupled physics model has been developed and validated for predicting the performance of the MEMS accelerometer. Results from simulations are with difference of 10%.

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