Optimization of Microstructures Used in CMOS-MEMS Sensors Based on Topological Design Process

J. Mares-Carreño*[1], G.S. Abarca-Jiménez[2], and M.A. Reyes-Barranca[2]
[1]ESIME-IPN, [2]CINVESTAV-IPN,
*cmaresj@live.com

Abstract: This paper focuses on the topological design process of microstructures used in CMOS-MEMS sensors in order to establish the best features of mechanical performance. The structures here described can be fabricated using the design rules from standard CMOS process (On-Semiconductor 0.5 microns, N-well, double polysilicon, double metal), followed by a sacrificial layer etching needed for the structure release. Two cases are shown, a stationary mechanical analysis and a stationary electro-mechanical analysis, using the optimization module, solid mechanics and electromechanical COMSOL Multiphysics®. The procedure used in this work is to define the effective area intended for the microstructure and given the operating conditions and restrictions of movement, an approximation of the geometry of the sensor anchors is obtained, for then apply design rules established by the manufacturer.

Keywords: topological design, CMOS-MEMS, electro-mechanical analysis.

1. Introduction

In the world of semiconductors one of the most popular and widely used technologies is the CMOS (Complementary Metal-Oxide Semiconductor) manufacturing process. Since there are several similar fabrication steps in (CMOS) technologies and the Micro-Electro-Mechanical Systems (MEMS), a derivative technology has been called CMOS–MEMS. Using this technology the sensors and actuators are fabricated in the same substrate.

One of the most common transduction principles used in CMOS-MEMS is the principle of capacitive transduction because of its many advantages. In the same extent that the capacitive structure improves performance its geometry complexity increases.

When a CMOS-MEMS device is designed the effort is focused in the electrical performance since the mechanical design has many more restrictions due to the nature of the manufacturing process.

This work is focused on obtaining structures for capacitive sensors that can be manufactured using standard CMOS technology, with good mechanical characteristics setting only target performance restrictions, without the need to carefully calculate each part and respecting the manufacturer's design rules.

2. The Capacitive Structures

The capacitive structures for the devices described in this work are based on design rules of a standard CMOS process (On Semiconductor 0.5 microns, N–well, double polysilicon, three metal layers). Thereby, thanks to the double layer of metal offered by this technology, the sensor can be fabricated.

For generating the capacitive sensor an analogy to a parallel plate capacitor is made and two elements are considered: a no-moving element in the role of the fixed electrode and a moving element in the role of seismic electrode. The seismic electrode is responsible for transducing the physical variable to be measured in to a variable capacitance. This kind of configuration in widely used in inertial sensors such as accelerometers, gyroscopes and pressure sensors. Fig. 1. There are two basic ways to generate a capacitive sensor. Using a non-moving electrode in a parallel plane (Fig. 2) or by using a perpendicular no-moving electrode (Fig. 3).

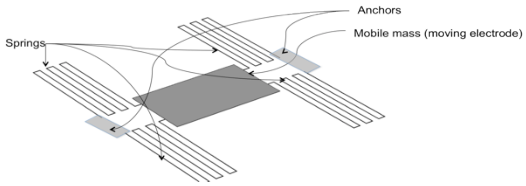

Figure 1. The typical moving electrode for MEMS sensors.

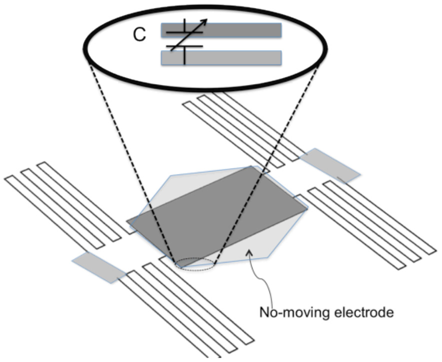

Figure 2. Capacitance sensor with a non-moving electrode in a parallel plane.

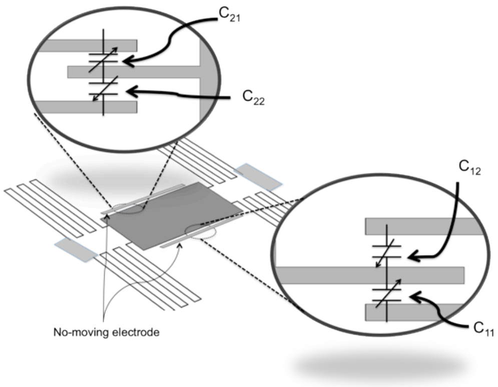

Figure 3. Capacitance sensor with a non-moving electrode in a perpendicular plane.

2. The topological design

Engineering design it's a tough iterative process, since for every design problem there are several needs to fulfill and restrictions to look up, and usually some are mutually exclusive, which means that if the designer wants to meet one goal has to let some other behind. On the other hand the design task in engineering have always pursue the best result possible, namely "the optimum" for the specific problem in turn.

The problem of engineering design stated before results challenging in every single branch of engineering, but when a designer face up a problem which involves knowledge from a variety of engineering branches the problem complexity grows up exponentially, this is the case of MEMS design where mechanical design meets microelectronic design.

Topological optimization is widely used in different areas of science and engineering, as is the case of (Perini, Luciano, & Corso, 2016) where it is used to optimize a market model, and the case of (Laudani, Fulginei, & Salvini, 2014) in this case it is used to solve a problem of computer science. In the case of this paper topological optimization will be used to generate a mechanical design of a MEMS sensor.

In the specific case of inertial MEMS the mechanical design turns out to be a key factor in the final performance of the sensors, needing so special attention. The main goals to achieve in the mechanical design of inertial MEMS are to minimize volume and mass globally and improve stiffness in the direction or directions of interest. Given the above, mechanical design of inertial MEMS can clearly be seen as a task of structural optimization, and since we can vary sizing and shape of the structures, a topology optimization process is suitable.

The SIMP method was implemented in order to achieve the goals after mentioned. Recalling that in the SIMP method the density is used as the design variable for the optimization problem which interpolate between zero and the Young modulus of the material.

The purpose of the model is to minimize the weight of the domain setting a minimum rigidity, limitating the domain displacements in a desired direction.

3. Use of COMSOL Multiphysics® Software

COMSOL Multiphysics® was used in order to apply a topology optimization process to a MEMS structure, for which the Solid Mechanics and Optimization modules were used. The first step was to propose a design space at which some boundary conditions were applied and a first stationary study was solved obtaining some results like the initial displacements and Von Mises stress.

For the development of this work two modules area used: Solid Mechanics in order to represent the spring holding the movable mass and the Optimization module for the topology optimization process on the supports of the moving mass.

To start the optimization process a design variable is created as a Control Variable Field over the whole design space. The variable design is initialized to one and seeks to minimize. As was mentioned early in the SIMP method the density is used as the design variable, so it`s needed to relate the density with control Variable field, this is done using a mass properties node. To relate the design variable and the domain to be optimized an integral objective which relates the Control Variable Field with the mass properties is applied in the domain. The domain is restricted using a Point Sum Inequality Constrain over the points at the free end of the design space establishing a maximum displacement, in this way the minimum desired rigidity of the domain is stated.

The SIMP method requires a penalty variable. For a proper performance of the SIMP method the penalty factor must have a minimum value which is calculated based on material properties (Bendose, Sigmund, 2004) it is well kwon that besides the penalty factor a mechanism to avoid mesh dependency must be used in order to obtain better results in topology optimization process but nevertheless in the designs that are shown later this mechanism for mesh independency is omitted, the idea was to take advantage of the checkerboard phenomena in the topology results as for simplify the interpretation and translation of this results to a CAD model, well then a mesh composed of squared elements with length sides that are lambda multiples (where lambda is a technological parameter of the CMOS process) is imposed over the design space.

On the other hand, the Solid Mechanics Module is used to model the holding element of the movable mass. Since this element is represented by a beam fixed on one side and attached to the mass at the other end, a fixed constrain is used on one end and a boundary load on the other end. Two different designs are presented one with a boundary load due to a 250g force and other due to a 16g force, both loads are calculated based on a square seismic mass of 1000 microns per side and considering four symmetrically distributed supports for the seismic mass. Its important to recall that a electromechanical analysis was carried out in order to estimate the displacements due to a electrostatic actuation in a sensing structure, those results can be seen in figure 4 and it results that the displacements obtained in the electromechanical analysis are negligible regarding the final displacement desired for the sensing structures which is 0.5 microns therefore the effects of electrostatics actuation were ignored for subsequent models.

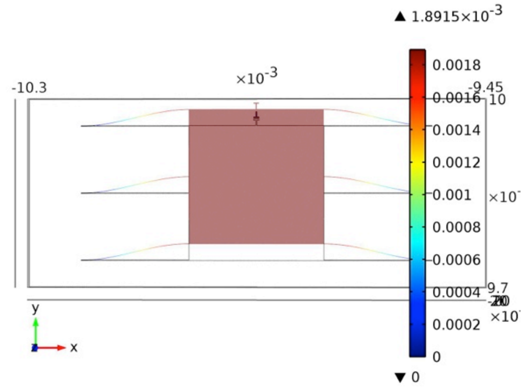

Figure 4. Displacements due to electrostatic actuation

The solve of the problem was carry out using a continuation method were the penalty factor was increased gradually once the penalty factor reaches its final value a gradual refinement of the mesh is performed so as to obtain finer results.

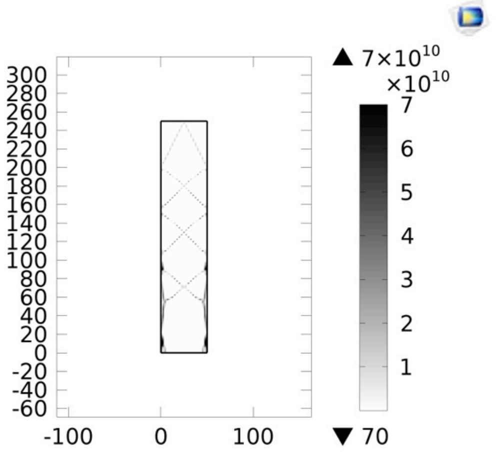

Figure 5. Results of topology optimization for the 250g force.

The approach aforementioned was used initially in 2D models obtaining the results of the figures 5 and 6 where the proposed space design is a solid rectangle of 50 microns per 250 microns for figure 5 and 10 microns per 250 microns for figure 6.

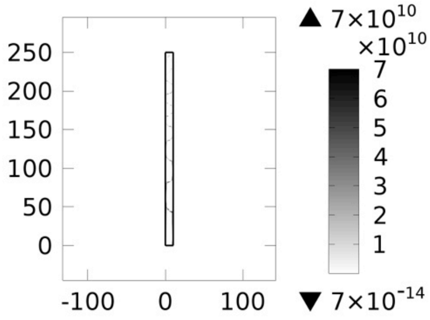

Figure 6. Results of topology optimization for the 16g force.

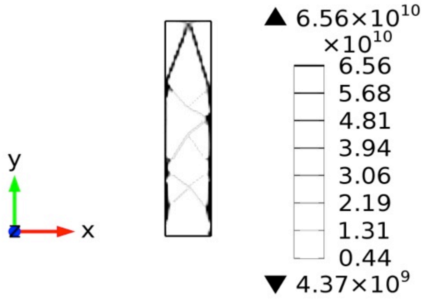

Figure 7. Results of topology optimization for the 250g force (3D model).

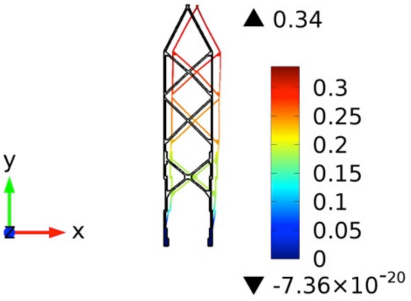

Figure 8. Displacements for the proposed CAD design

After the optimization of the 2D models was completed 3D models were constructed and analyzed also, but for the 3D models only the force of the 250g acceleration was taken into account since it was the primary focus of the project. The results of a 3D model is shown in figure 7.

With the results of figures 5 and 7 new CAD models were drawn an the analyzed using the Structural Mechanics module so as to test out its performance, obtaining the results of figure 8.

8. Conclusions

Topology optimization can be used in the design of inertial MEMS structures in order to obtain good approximations of the material distribution that assures the desire performance of the structures, something that should be taken into account in this process is that the forces owing to the accelerated seismic mass are of the order of 10e-7 N or even less so that the design spaces proposed must be small since large design spaces tends to result in material percentages that drops below 1% which in turn results in convergence problems.

On the other hand not using a mechanism for mesh independency helped to a faster construction of a CAD model from the topology optimization results but nevertheless the effects of not include the aforementioned mechanism must be studied in depth, because as it is shown in figure 8 the resultant geometry is more rigid than expected.

Finally the effect of the weight of the seismic mass on out of work plane the deflection must be taken into account maybe as an optimization objective.

9. References

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