Simulation Tools Used in Micro-Electro-Mechanical Systems. A Case Study on a Non-Conventional SOI-MEMS Structure

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Abstract—**The MEMS structures represent a milestone in the actual bioengineering and micro-fluidics area. Simulators are necessary for the students training or for specialists at the design stage. This paper presents some tools and their applications for the simulation of an integrated micropump, achievable in the SOI technology. The simulations results intend to emphasize the tools performances and functions with example on the proposed SOI-MEMS structure. Furthermore, the paper is focused on the software facilities and possible lab them as a contribution to the learning technologies.**

Index Terms—**devices, ducts, membrane, simulator.**

I. INTRODUCTION

The Micro-Electro-Mechanical Systems (MEMS) structures were extensively developed in the last ten years due to their demand in applications like Lab On Chip [1], biosensors [2], integrated micropump and actuator, [3].

The simulation tools for these complex devices are borrowed from different domains. For instance, in a technological design stage, tools like Suprem, Athena can be used. They are able to follow the structure from the first simple Si wafer, up to any etched geometry in silicon. During the silicon micromachining, simultaneously with the mechanical shape etchings, some electronics devices are developed in the upper layers, [4]. In order to simulate an electrical behavior of these kinds of devices, some tools like Medici, Atlas are recommended. For the non-conventional devices, like a MOS transistor with piezoelectric material included in the gate space, which become a pressure sensor, combined functions are required, [5-6].

Any mechanical shape and geometry can be fulfilled with the Si-technology micromachining. One of the preparation methods of a thin membrane, consists in a back etching of a Silicon On Insulator (SOI) wafer, [7].

Our paper presents the Coventor applications on this kind of atypical device. The analyzed main structure is a non-conventional SOI-MEMS micropump, that combine a Silicon On Oxide membrane as actuator and a diffuser / nozzle mechanical device as microfluidic ducts. The advantages of the SOI structure included in the MEMS device are: (1) the buried oxide is an excellent etch stop layer for the membrane preparation, (2) perfect electrical insulation of the upper integrated actuator, from the fluids that flow through the ducts beneath the SOI film.

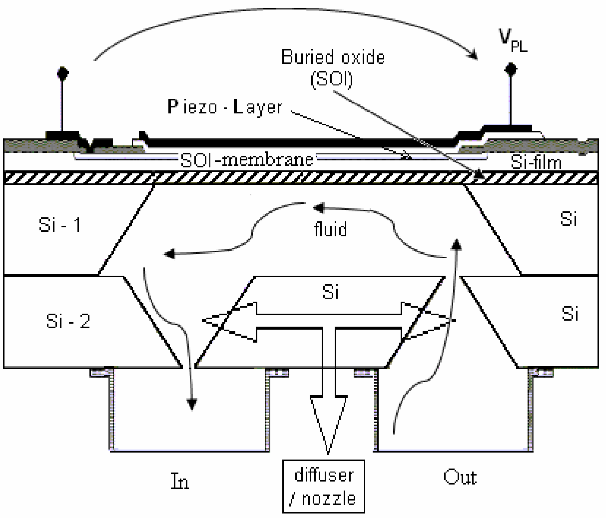


Figure 1. The basic structure of the studied MEMS

II. THE MEMS STRUCTURE

Figure 1 presents the basic structure of a MEMS micropump, working with a piezoelectric layer, placed on a thin membrane as actuator. In this way, the electrical device is integrated in the upper wafer (Si - 1) and the micropump chamber is integrated in the bottom wafer (Si - 2).

The starting step for the Si - 1 is a SOI wafer. In a second step follows a back etching to perform the thin membrane, where is finally enclosed a piezoelectric layer. The Si - 2 wafer is micromachined, so that, the diffuser and the nozzle ducts are achieved. Both parts, Si - 1 and Si - 2, are easily bonded in the silicon technology, [8].

In order to bring liquid from the input chamber into the pump chamber, an AC signal must be applied, V_{PL}. During the positive bias V_{PL}, the Si-membrane is down-bending and the chamber volume decreases; now the outlet acts as a diffuser and the inlet as a nozzle. A larger volume of liquid is transported out of the chamber through the "Out" duct than through the "In" duct (the pump mode).

When V_{PL} voltage becomes negative the membrane is up bending and the chamber volume increases because a larger volume is transported into the pump chamber through the inlet that acts as a diffuser, than through the outlet that acts as a nozzle, (the supply mode).

III. A STATICAL MEMBRANE SIMULATION

In order to simulate the mechanical stress in a thin membrane, the software can apply a force in a point, a pressure on a surface, or an electrical stimulus for a piezo-electric material. In our case study, a square membrane was firstly defined. The input data were: the membrane size 1000µm x1000µm x10µm, the materials constants and the limit conditions - embedded edges - in our case. Appling a voltage V_{PL} = +1V ÷ +5V over the piezo-layer, a down-banding of the membrane occurs, [9]. The simulated maximum stress in membrane, S_{xy} is 0.5MPa << 10MPa - the failure stress in silicon, fig.2.

The simulation result, in a cross-section of the square membrane, at the same V_{PL}=5V, is available in fig. 3.

Secondly, a circular membrane with 1000µm width and 10µm thickness, containing a centered 600µm width piezoelectric material, was simulated. The input stimulus, V_{PL}, was in the same range 0V ÷ +5V. Figure 4 presents the membrane deflection under V_{PL}=5V.

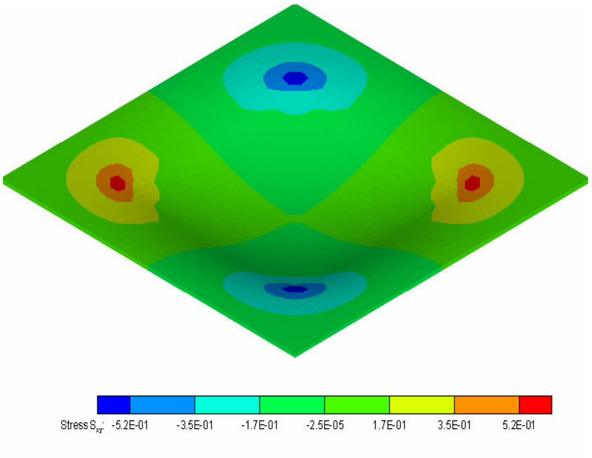


Figure 2. The Si-membrane stress when V_{PL}= 5V

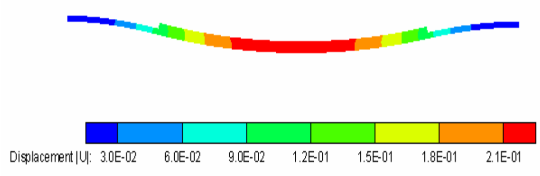


Figure 3. The membrane displacement on vertical direction in a cross-section, with x 100 exaggeration on Oz axis

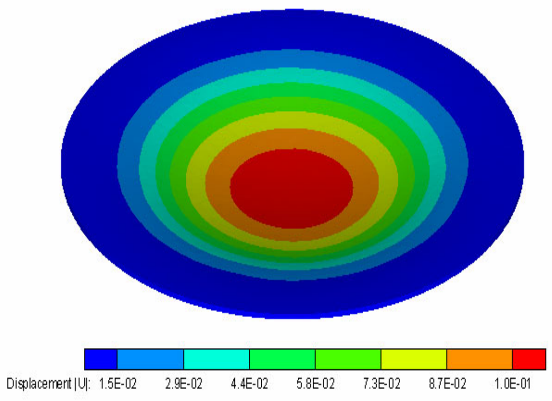


Figure 4. The deflection of the circular membrane at 5V

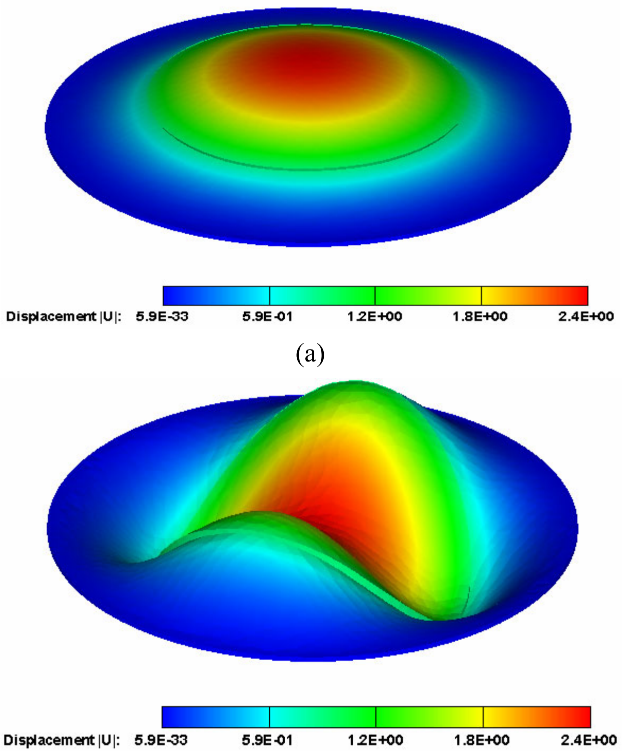
In this way, can be selected the optimal shape for the membrane, in order to achieve the maximum deflection at the same stimulus, keeping the device far away from the failure conditions. In our case, the square geometry is more convenient, due to the deflection.

IV. A MODAL ANALYSIS

The modal analysis studies the dynamic properties of the membrane under vibration excitation. The simulator takes into account the first five mechanical vibration modes that were presented in the table 1 and fig. 5, a-b.

TABLE I.
THE MODAL ANALYSIS FOR THE CIRCULAR MEMBRANE

Vibration Mode	Frequency (kHz)
1	24.42515
2	55.51500
3	55.93739
4	96.52207
5	97.85767



(a)

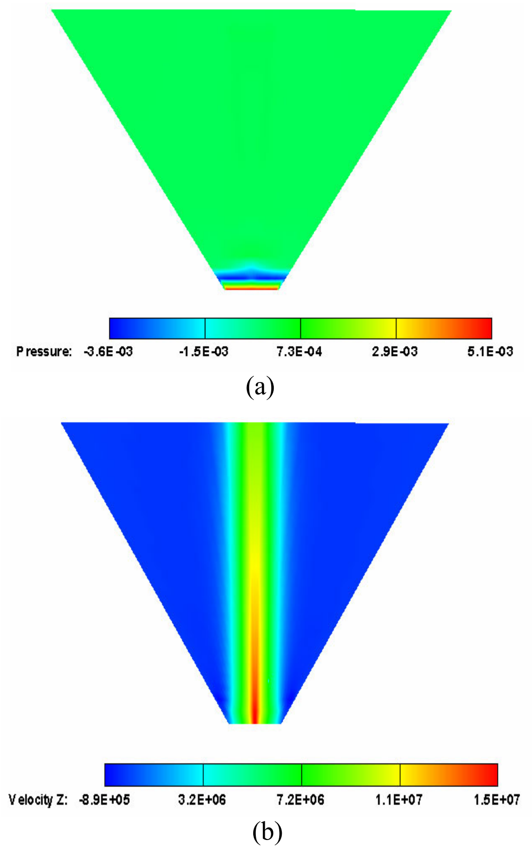
(b)

Figure 5. The vibration mode in the circular membrane: (a) the first mode; (b) the fifth mode; displacement given in microns

The previous figures prove that neither harmonics don't damage the membrane: the maximum displacement is 2.4µm, still far away from the failure conditions.

V. MICROFLUIDICS SIMULATION

For the micro-fluidics domain the software can simulate isolate or complex fluids ducts, [10]. A diffuser is an expanding duct and a nozzle is a converging duct. Figures 6 provide the simulation result regarding the flow through a diffuser contained in the MEMS structure from fig. 1.



(a)

(b)

Figure 6. The diffuser case: (a) The pressure; (b) The fluid velocity on Oz direction

As input data must be specified the geometry of the ducts - a pyramid trunk shape with sizes: l = 100µm, L = 736µm, H = 450µm, where l is the small base length, L is the big base length and H is the height of the pyramid trunk. The flow sense depends on the difference of pressure, once positive, when the valve acts as diffuser and secondly negative, when the valve acts as nozzle. The liquid pressure distribution is available in fig. 6.a and the velocity magnitude of the liquid particles is shown in fig. 6.b, for a pressure difference applied on the duct edges, equal with 0.005MPa.

The pressure loss in diffuser / nozzle p_n, p_d, is depending on the pressure-loss coefficients $\zeta_{n,d}$, the fluid density ρ and the fluid flow velocities v_{n2}, v_{d2} in the throat, extracted from simulations. Their analytic expressions are given by, [11]:

$$p_d = \frac{\zeta_d v_{2d}}{2}\rho \text{ and } p_n = \frac{\zeta_n v_{2n}}{2}\rho . \qquad (1)$$

Using the pressure p_n or p_d at a given section, besides to the velocities distribution at the same section, from fig. 6 and knowing the fluid density, the pressure-loss coefficients $\zeta_{n,d}$, can be estimated with (1), for the selected geometry.

VI. MICROCHANNELS SIMULATION

Sometimes, in applications like Lab On Chip, a very low quantity of fluid (µl – pl) must be transported, [12]. In this case the output valve is replaced be a micro-channels network, fig. 7. The fluid flow analysis is possible in this case, using the previous simulation tools, too.

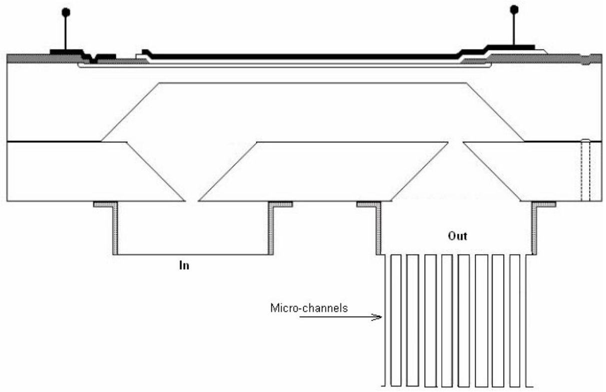


Figure 7. The micro-channels network

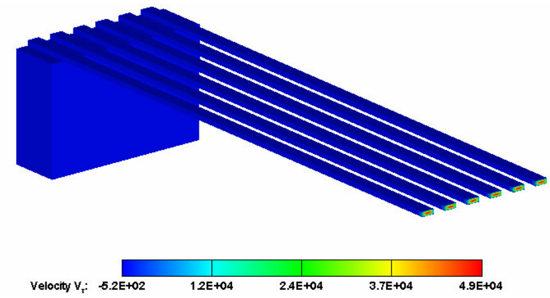


Figure 8. The fluid velocity through the micro-channels network

The micro-channel sizes were: length of 2000 µm and the cross section of one channel was 50 µm x 20 µm.

In this case, the fluid flow was studied for all the microchannels, when the same pressure difference was applied to edges, fig. 8. The final scope in microfluidics is to estimate the micropump flow, expressed in µl/s. Therefore, the main investigated output function is the fluid velocity at the inlet and outlet chamber. Appling a pressure difference about 0.008MPa, the net flow 102 nl/s was achieved with this kind of micro-channel network.

Figure 9 shows a detail of the fluid velocities distribution in a cross-section of a micro-channel. A first result shows us that the fluid passes through this micro-tube, where the capillarity could reject the liquid. The velocity vectors presented in this picture are parallel in the middle region, proving a laminar flow. Near walls the velocity becomes negative, suggesting a reverse sense of the particles, accordingly with the Reynolds' theory, [13].

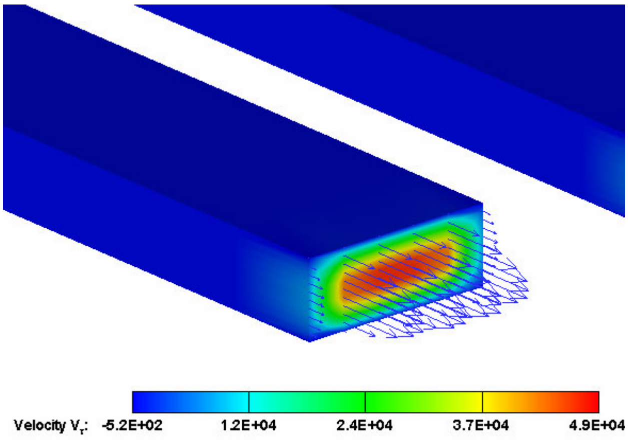


Figure 9. The fluid velocity at the output section of a micro-channel

These MEMS simulation tools can provide some lab themes for the master studies in the technical universities, [14]. A first subject concerns the electrical analysis, establishing the incoming stimulus that must actuate an embedded membrane. Another lab them regards the duct geometry optimization, in order to accomplish a minimum time for the micropump chamber loading and ensuring minimum loss pressure. Special topics can refer from micro-valves and micro-channels up to Nano-Electro-Mechanical Systems (NEMS).

VII. CONCLUSIONS

This paper described the simulation tools used for general MEMS parts: membrane deflection under electrical stimulus, liquid flow through some diffuser-nozzle ducts under mechanical stress, a micro-channel network. Some simulation results are available for a particular MEMS structure. There are presented: the input data for a given architecture, some design rules and Coventor simulation results. These tools are used in industry for the MEMS simulation and design, but they are powerful learning instruments and helpful tools for the virtual analysis of new MEMS structure in the academic environment.

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