Design and Analysis of a MEMS Variable Capacitor using Thermal Actuators

Diseño y Análisis de un Capacitor Variable MEMS utilizando Actuadores Térmicos

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Abstract

We present the design and analysis of a MEMS variable capacitor coupled to thermal actuators. The variable capacitor is composed by two main components: 1) the capacitor built by two squared plates, which one plate is mechanically fixed to the substrate and the other is a moving plate having mechanical suspensions (springs) connected from each corner of it to the substrate, and 2) a set of thermal actuators that push the moving plate away from the substrate. Depending on the power applied on the thermal actuators, these would push up the variable plate from its sides, while the suspension pulls the plate down to the substrate for equilibrium. This work includes the design fabrication steps using PolyMUMPS™ process, and provides tables for the resulting values of the variable capacitors. The results accomplished using COVENTORWARE™ software show that the variable capacitor has potential for automatic compensation of capacitances and for integration into frequency oscillators and filters.

Keywords: MEMS Design, MEMS FEA, Variable Capacitors, Thermal Actuators.

Resumen

En éste trabajo presentamos el diseño con tecnologías MEMS y análisis de un capacitor variable acoplado a actuadores térmicos. El capacitor variable está compuesto por dos componentes importantes: 1) el capacitor construído de dos capas cuadradas paralelas, en donde una placa está mecánicamente fija al sustrato y la otra es una placa movible la cual tiene resortes flexibles conectados de cada esquina de la placa al substrato, y 2) un arreglo de actuadores térmicos que separan la placa movible del substrato. Dependiendo de la potencia aplicada a los actuadores térmicos, éstos empujaran la placa variable por las secciones laterales para separar la placa del substrato, mientras que los resortes de suspensión contrarrestan la fuerza mecánica para mantener el equilibrio. Éste trabajo incluye los pasos de diseño y fabricación utilizando el proceso PolyMUMPS™, y proporciona tablas de los resultados obtenidos destacando la funcionabilidad de los capacitares variables. Además, se presentan los resultados obtenidos utilizando el software COVENTORWARE™, donde mostramos el potencial de uso del capacitor variable para la realización de compensaciones automáticas de capacitancias dinámicas para la integración al desarrollo de osciladores de frecuencia y filtros.

Palabras clave: Diseño de MEMS, Análisis de elementos finitos de MEMS, capacitares variables, actuadores térmicos.

1 Introduction

Telecommunications and Radio Frequency are fast growing technological areas. Recent development of computers, PDAs, wireless phones, GPS systems, even toys are rapidly evolving and supporting complex computational and signal processing power to final users. Most of the advances in communications are thanks to the advances in the development of MicroElectro-Mechanical Systems (MEMS.) Generally, MEMS brings together different kinds of technology while developing devices systems. Some examples of this are combinations of electrical-mechanical, mechanical-optical, optical-electrical, mechanical-fluidics, electrical-fluidics, electro-thermal, and so forth.

One set of specific devices that are supporting the advances of communications through MEMS technology is composed of capacitors, resonators and filters. These devices can be built to get high Qs of above 1 GHz ranges. For example, Young et.al in [1] fabricated a 2 pF variable capacitor and ranging capacitances for low voltages (3 V.) Their concept involved a simple suspension system that reacts depending on the applied DC voltage bias or constant electrostatic field. Jiménez et.al in [2], suggested using IC-compatible Dickson charge pumps to control the variable capacitance of capacitors. This later work is related to the optimization of charging variable capacitors, and handling them. Xiao et. al. demonstrated in [3] the feasibility of using fixed combs to move a capacitor plate with respect to other, therefore obtaining variable capacitance. The only problem with this approach is the need of high voltages in the driving circuit that affects also the charging and capacitance capability of the capacitance varying device. However, Seeger and Boser demonstrated in [4] (similar results to those presented in [6]) that charge control in plates can create a series of different problems that induce instability in the parallel plates, including parasitic capacitance. Investigation of coupling DC bias and AC voltages while calculating capacitance measurements is critical [7]. An interesting phenomenon would be to couple mechanical forces (not DC Bias force) to neutralize ac signals while measuring capacitances (intention of this work.) Moreover, the coupling of mechanical parts and electrostatic charges in the designs of specialized sensors, including sensors to force feedback loops has been investigated by Handtmann et. al. in [8]. These works couple several areas of research, and their merging requires deep understanding using not only electrical field domain, but also physics, mechanics and other areas.

This work presents the design of a variable capacitor using MEMS technology. The design is divided mainly into two parts: 1) design of the electrostatic capacitor plates with suspension, and 2) design of a set of thermal actuators [10,11] that push-up the moving plate. This work, as a difference to the one presented by Harsh et.al in [9], is that they do use a simple suspension system directly connected to the thermal actuators in the mechanical connection to the moving plate, and which actuators are, by the way, different design. The analysis of combining these main areas of electrostatic and mechanics merge in this work. Mainly, the result from a set of three different thermal actuators, varying its length is correlated to four different plates with different suspensions. The combination of these different actuators and plates provides a table showing the capacitance variation of the capacitor, given the different variables. Moreover, the fabrication technology PolySilicon Multi-User-MEMS-Process-System (PolyMUMPS™) used to manufacture the devices designed / analyzed / tested in this work is revisited here.

2 General Design

The variable capacitor of this work uses two main components: 1) a set of plates composing the capacitor, where one plate is fixed and the other is a moving square plate having mechanical suspension composed of springs connected through the corners of the plate, and 2) a set of electro-thermal actuators that push the variable plate away from the substrate. The main concept design of the variable capacitors is shown in Figure 1. It is composed of two parallel plates, the lower plate is fixed to the substrate, and the upper plate is the moving plate and it is fixed through a suspension from its corners. Four springs compose the suspension, and these are mechanically fixed to the substrate and they counteract with mechanical force to balance the pushing-up forces applied to the sides of the plate (shown as arrows in Figure 1.) The pushing-up forces are applied through the electro-thermal actuators. The balance of the forces, the variable mechanical force produced by the electro-thermal actuators and the counter reacting mechanical force of the springs makes the moving plate steady and so its capacitance with respect to the lower electrostatic plate.

Using the PolyMUMPS fabrication process from MEMScAP, we designed and fabricated this concept idea. The advantages of using this PolyMUMPS process are: 1) low cost; 2) it provides three different surface micromachined layers of Polysilicon, two of these layers can be mechanically separated from the base substrate; and 3) it provides a thin film of gold for electrical interconnect and/or optical reflectivity. Another advantage of this process is that since this technology is widely used in academia, good material properties are available in literature to accomplish suitable MEMS FEA design analysis in tools like MEMSPro, IntelliSuite, and Coventorware.

The three polysilicon layers of the PolyMUMPS process are electrically conductive. One of these layers is hold to the substrate and is used as an electrical/electrostatic layer (Poly0) and the two others are mechanical layers that can be separated from the substrate (Poly1, and Poly2). Figure 2 shows a more detailed drawing of the variable capacitor designed in this work.- It shows four electro-thermal actuators intended to push up the upper plate from its sides; it shows the four springs composing the suspension of the variable capacitor, and the electrical contacts of the upper (variable) and lower (fixed) plates. The following sections provide detailed descriptions of the capacitor's elements.

Figure 3 shows the cross section of the deposition layers used in the design of the variable capacitor. Figure 3 shows the following sections: section 3a shows the hot arms cross section view highlighting the pads (note A^1 in the figure,) the interface section view (note A^2 in the figure,) and the capacitor plates (note A^3 in the figure;) section 3b shows the cold arms cross section view highlighting the anchoring to the substrate (note B^1 in the figure,) the cross section view highlighting the height of the cold arm in the interfacing section (note B^2 in the figure,) and the capacitor plates (note B^3 in the figure;) and section 3c shows the cold arms cross section view highlighting the suspension system (shown by notes C^1 and C^3 in the figure,) the capacitor plates (note C^2 in the figure,) and the pad used to connect the voltage for the upper plate of the capacitor (note C^4 in the figure.) The PSG layer is the sacrificial layer that is etched away to let the capacitor and actuators be controllable.

3 Electro-thermo-Mechanical Actuators

The thermal actuators, or electro-thermo-mechanical actuators, use resistive (Joule) heating to generate thermal expansion and movement. The main elements are: 1) the electrical pads, 2) the hot arms, 3) the cold arms, and 4) an interfacing section (see 3D Figure 4.) Current is passed to the arms via the pads. The higher current density in the narrower (hot arm) results in a greater ohmic heating causing it to expand along its length. The hot arms drive the current and are electrically connected through the interfacing section. The current flowing through the hot arms creates heat. Due to the thermal expansion coefficient and the Joule principle of the hot arms' material, they push over the interfacing section of the actuator. In contrast, the cold arms are directly fixed to the substrate from one end (not electrical connection to pads,) and are mechanically connected to the interfacing section. Since there is no electrical contact from the pads to the cold arms, these arms do not drive any current and therefore do not expand as the hot arms expands while driving current. The difference in thermal expansion generates a pushing force pointing up in the interfacing section. The reason is that the mechanical connections of the cold and hot arms in the interface section are different (see Figures 3 and 5.) Therefore, the pushing force by the hot arms in the lower part of the interface section creates a momentum force resulting in a pushing-up force to the end tip of the actuator.

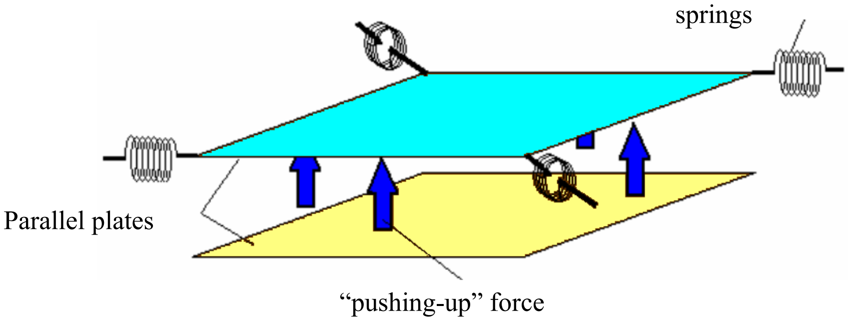


Fig. 1. Concept design of the variable capacitor.

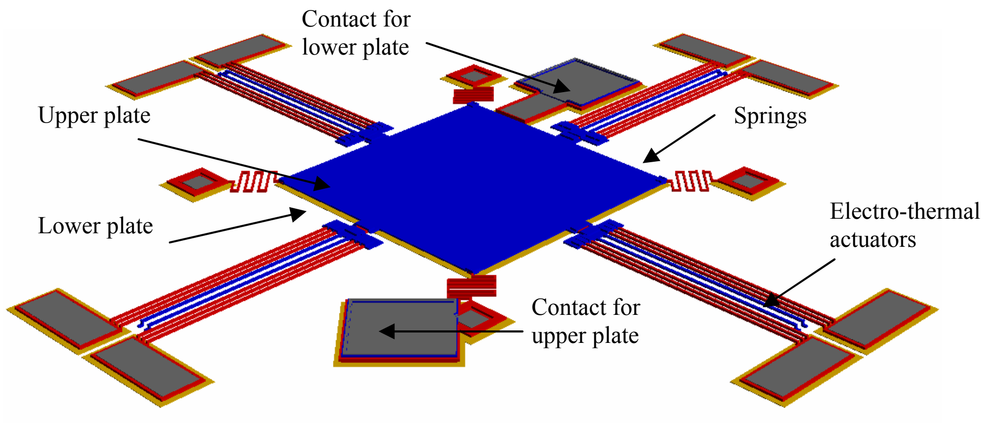


Fig. 2. Main components of the variable capacitor.

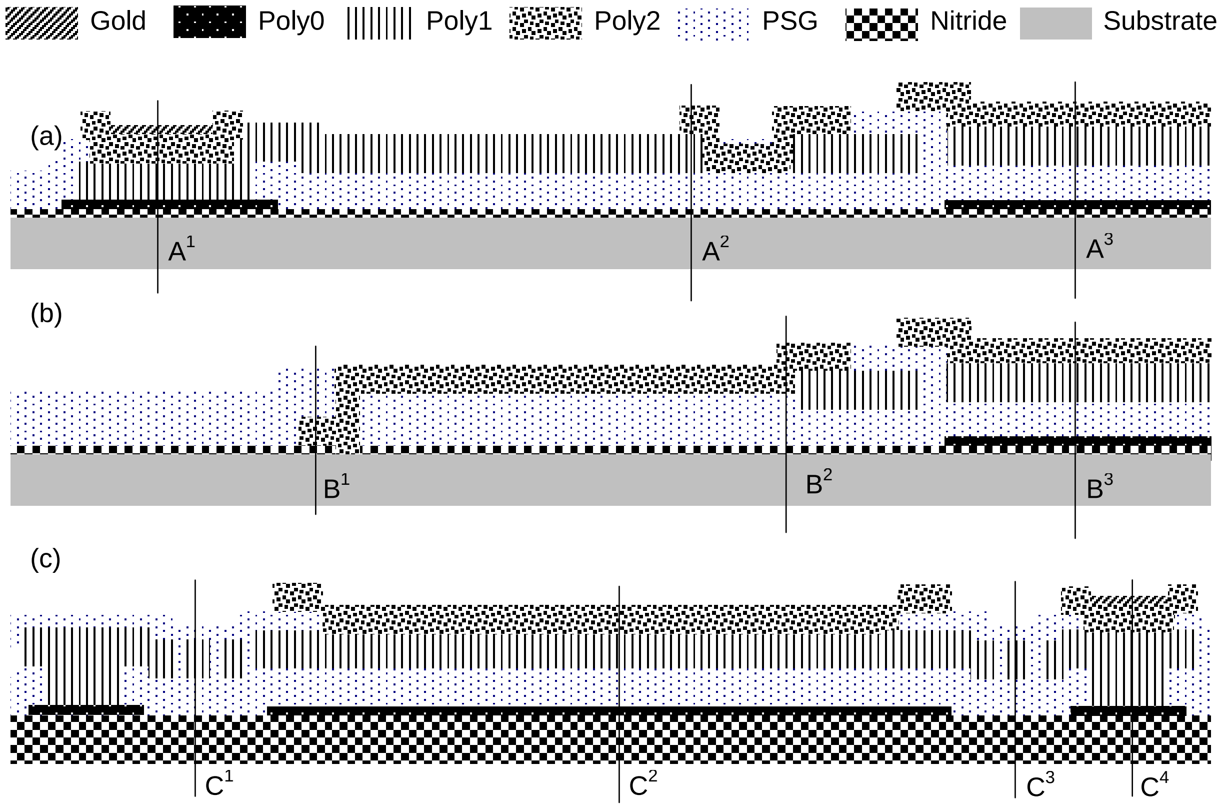


Fig. 3. PolyMUMPS process' layers for the variable capacitor design.

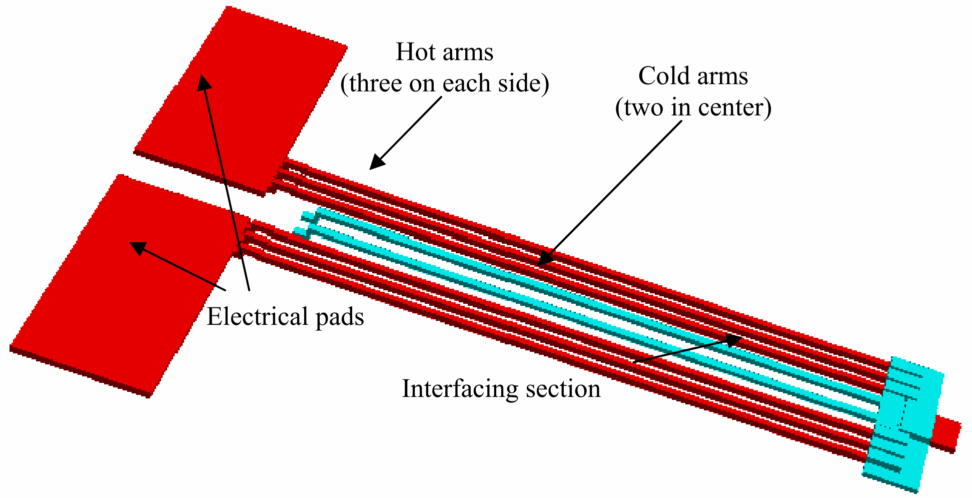


Fig. 4. Main components of the electro-thermal actuators.

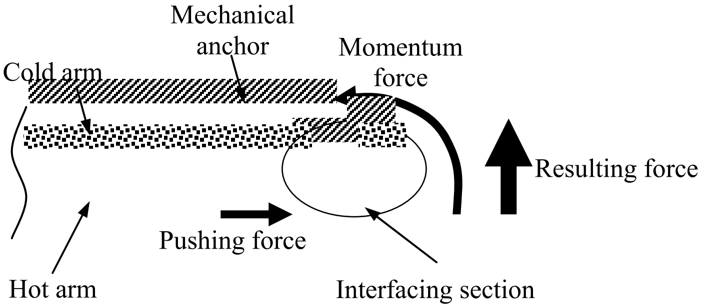


Fig. 5. The hot arms are pushing a little bit lower in the interfacing section, with respect to place the cold arms are connected.

Table 1 Material properties of PolySilicon

	Units	value
Young's Modulus (*E*)	MPa	$1.62 \text{ x}10^{5}$
Density	Kg/µm3	$2.23\text{x}10^{-15}$
Thermal Coefficient Expansion	1/K	$3.5\text{x}10^{-6}$
Thermal Conductivity	pW/µmK	$4.1\text{x}10^{7}$
Specific Heat	pJ/Kg K	$7.1\text{x}10^{10}$
Electric Conductivity	pS/µm	$5.0\text{x}10^{10}$

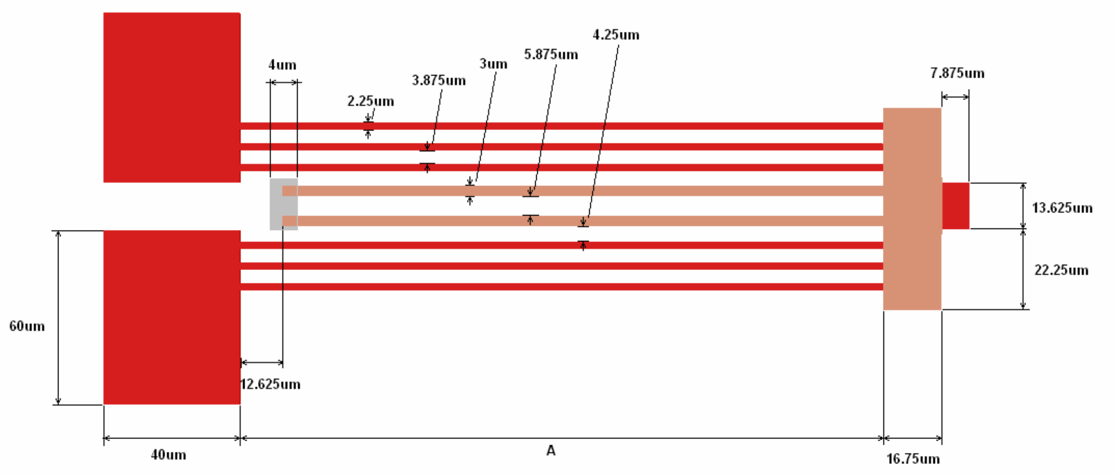


Fig. 6. The layout dimensions of the thermal actuators.

The 2D layout dimensions of the thermal actuators are shown in Figure 6. The different values for dimensions ‘A’ from Figure 6 were 150µm, 180µm, 220µm, and 250µm. By applying a potential in the pads of the actuators, current flows through the hot arms through the interface section, and the interface section pops-up from the substrate.

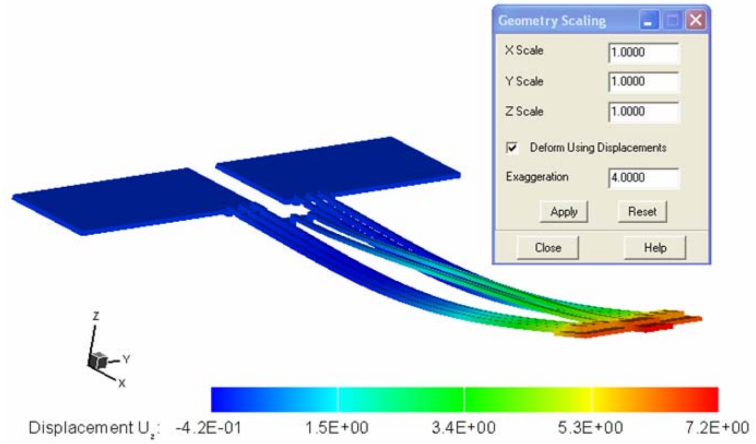
The FEAs were run using COVENTORWARE™ (specialized software for MEMS design and analysis) using the mechanical properties shown in Table 1. The resulting voltage in the interface would be half the amount of potential applied in the pads. Therefore, for each thermal actuator, if one pad is connected to ground (0 Volts), and the other pad is connected to *x* Volts, the voltage in the interface section would be *x*/2 Volts. For this reason, we applied *x* Volts in one pad and –*x* Volts in the other pad, such that the resulting voltage in the interface section are virtually zero Volts. The reader can guess now that our plan is to use the upper plate of the capacitor connected to the ground, and the lower plate connected to the positive or the negative voltage. Figure 7 shows the FEA analysis of one thermal actuator showing 7.2µm of displacement of the interface section. Table 2 shows five different voltages applied to one thermal actuator and the maximum temperatures resulted (the maximum temperature that polysilicon can handle is near the 900 degrees K.)

However, what would be the resulting force of the actuator? To answer this important question, we opted to insert a cantilever beam with known dimensions in the interface section of the actuator (separated 0.75 µm, which is the same initial distance the upper plate of the capacitor would be separated.) The dimensions of the cantilever beam were 2µm width, 2µm tall, and 100µm length. Running the same FEA analysis, but now including the cantilever beam, smaller displacements were obtained (as shown in the results’ section.) Figure 8 shows the 2D layout arrangement and how the interface section was closely connected to the cantilever beam. Given the displacements of the interface section pushing the beam, and using equations (1) and (2) we calculated the resulting forces of the corresponding actuators [10, 11].

$$F = 3EI\, y(L) / L^3 \tag{1}$$

$$I = 1/12\, w\, t^3 \tag{2}$$

where *I* is the moment of inertia, *w* is the width of the cantilever beam, *t* is the thickness / height of the beam, *y*(*L*) is the displacement in the Z direction, and F is the calculated force.


Geometry Scaling

X Scale 1.0000

Y Scale 1.0000

Z Scale 1.0000

☑ Deform Using Displacements

Exaggeration 4.0000

Fig. 7. FEA of thermal actuator, with exaggeration factor over the Z axis (lifting 7.2 µm.**)**

Table 2 Maximum temperatures shown in thermal actuator

Applied voltage	Maximum temperature
+1 and -1 Volts	317.35 K
+2 and -2 Volts	389.26 K
+3 and -3 Volts	509.10 K
+4 and -4 Volts	676.88 K
+5 and -5 Volts	892.60 K

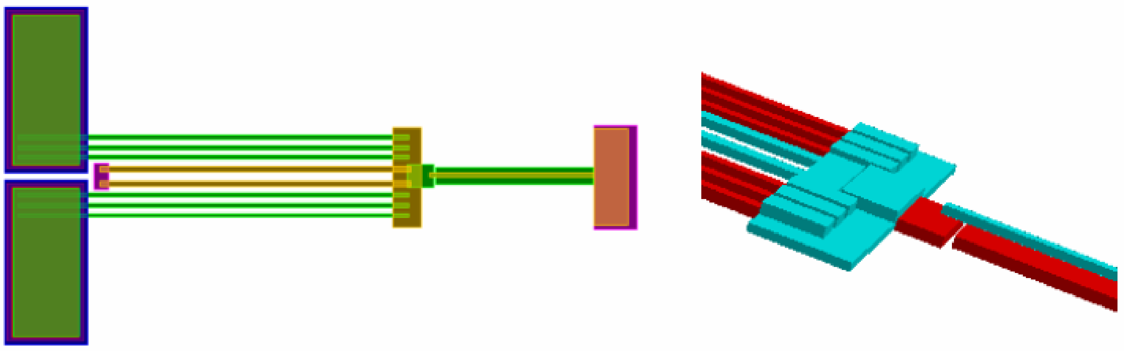


Fig. 8. Thermal actuator with a testing cantilever beam for calculation of pushing forces.

4 Capacitors with Mechanical Suspension

Given that we are working with a standard fabrication process, i.e. the PolyMUMS™ process, the capacitor considered in this design has the following variables: 1) 2D dimensions of plates, and 2) the suspension designs. This is, due to the fabrication process, we can not vary the thickness of the plates (explanation below,) and the initial separation of plates is fixed.

The PolyMUMPS™ process has one electrical layer (Poly0,) and two electro-mechanical layers (Poly1, and Poly2.) Given this, only two initial separations of plates can be used: two microns, for the sacrificial layer separation of 2 microns between Poly0 and Poly1; or the sacrificial layer separation of 3.5 microns between Poly0 and Poly2, in case Poly1 is not used in between. However, a resulting FEA analysis showed that for our designs, if the later case is used, the bending of the upper layer (Poly2) will complicate the parallel separation of the plates and will cause errors in capacitance calculation. Therefore, we opted to use the earlier case where an initial separation of 2 microns between plates Poly0 and Poly1 is used, and we included Ply2 over Poly1 to harden the above union of plates. Figure 3 shows the double plate used for the capacitor in cross sections A^3, B^3 and C^2, as well as it can show the two micron separation between Poly0 and Poly1 (cross section A^2, A^3, B^3) as a difference in the separation between layers Poly0 and Poly2 when not Poly1 layer is present (in cross section B^2.)

4.1 Mechanical Suspensions

We designed three different suspension systems for the variable capacitors. The suspensions are fabricated with the electro-mechanical layer Poly1, and their dimensions are shown in Figure 9. The only difference in the center and right designs is the number of “S” shapes involved, with respect to the left suspension dimensions. These suspensions are fixed to the substrate from one side, and hold the capacitor from the other side.

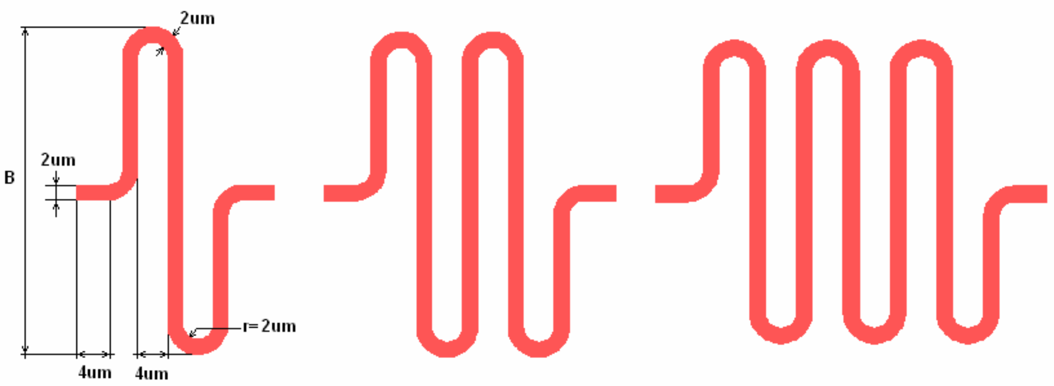


Fig. 9. Suspension designs for the variable capacitors.

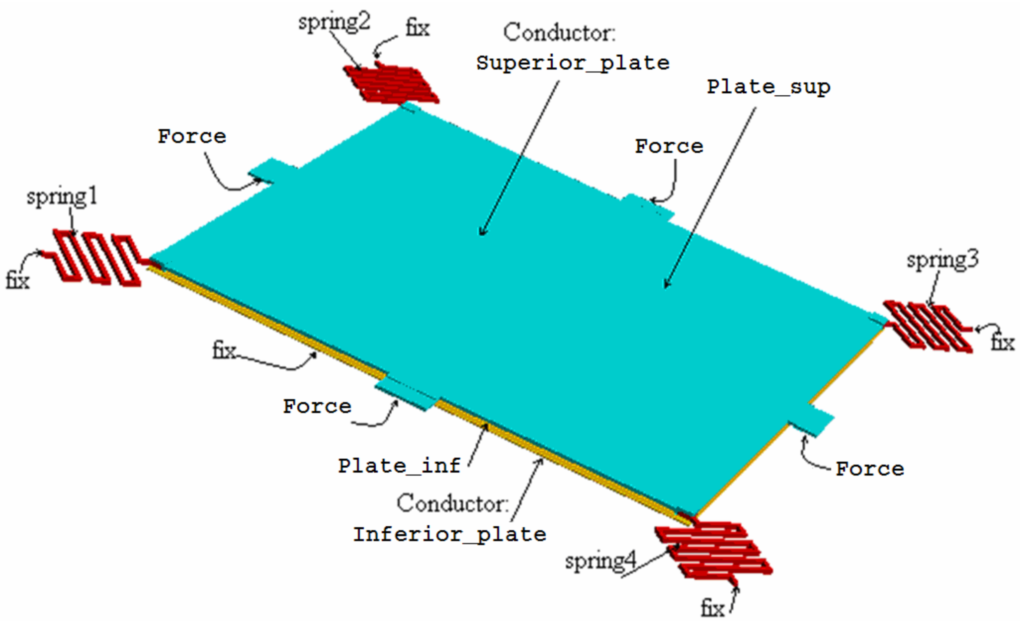


Fig 10. Variable capacitors' designs showing boundary conditions for COVENTORWARE™.

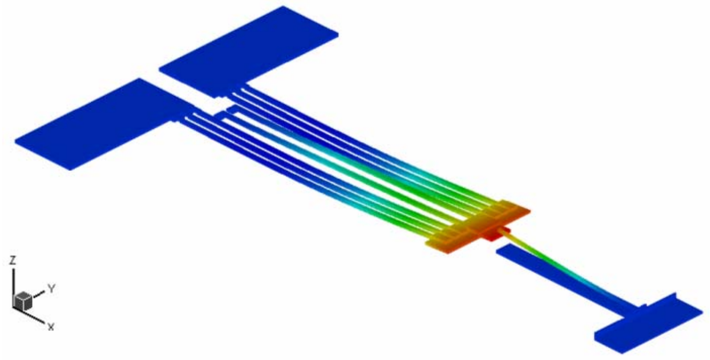


Fig. 11. FEA of thermal actuator with cantilever beam (lifting 3.5 μm.**)**

4.2 Variable Capacitor

Figure 10 shows the boundary conditions used to simulate and test the suspension systems for different forces applied on the sides of the upper plate. For example, the boundary condition shown as "Force" in figure is used to apply the pushing-up forces calculated in the thermal actuators' section. Also, the "fix" boundary conditions were used to hold mechanically the suspensions, as well as the lower plate of capacitor. The capacitance is calculated using the following equation [10, 11].

$$C = \varepsilon_0 A/d \tag{3}$$

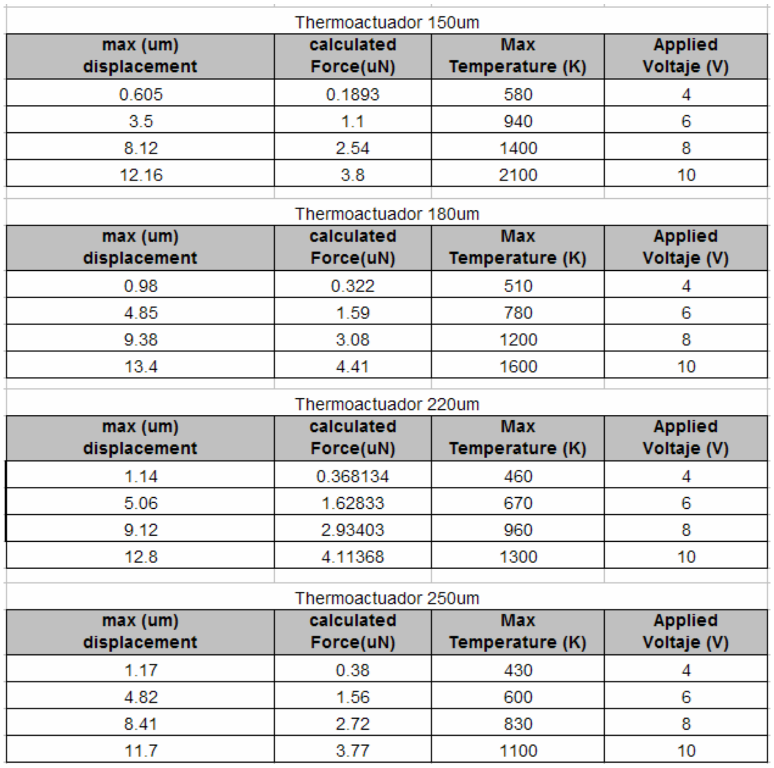
where A is the overlapping plate area, ε_0 is the dielectric constant of free air (8.854188 x 10^{-14} F/cm), and d is the plate separation.

5 Results

5.1 Resulting Forces from Thermal Actuators

The resulting displacements of thermal actuators mechanically coupled to the testing cantilever beams for different voltages are shown in table 3 (the voltages shown in this table are 2*x* Volts, after applying +*x* and –*x* Volts to each pad.) Figure 11 shows a displacement of 3.5 microns (as a difference with respect to the displacement on Figure 7, which did not have the test cantilever beam. Also, Figure 12 shows the corresponding displacement and pushing forces calculated from Table 3. In Figure 12, we can notice that the thermal actuators having 150µm and 180µm provide better rate of Force per Voltage applied. Thermal actuators having 220µm and 250µm start decreasing the power rate. This is due to the bending of larger hot arms compared to shorter actuators. This is, even if the larger hot arms grow a little longer compared to the shorter ones, they start bending more while the interfacing section moves up.

Table 3 Maximum displacements / temperatures and calculated forces.



Thermoactuador 150um

max (um) displacement	calculated Force(uN)	Max Temperature (K)	Applied Voltaje (V)
0.605	0.1893	580	4
3.5	1.1	940	6
8.12	2.54	1400	8
12.16	3.8	2100	10

Thermoactuador 180um

max (um) displacement	calculated Force(uN)	Max Temperature (K)	Applied Voltaje (V)
0.98	0.322	510	4
4.85	1.59	780	6
9.38	3.08	1200	8
13.4	4.41	1600	10

Thermoactuador 220um

max (um) displacement	calculated Force(uN)	Max Temperature (K)	Applied Voltaje (V)
1.14	0.368134	460	4
5.06	1.62833	670	6
9.12	2.93403	960	8
12.8	4.11368	1300	10

Thermoactuador 250um

max (um) displacement	calculated Force(uN)	Max Temperature (K)	Applied Voltaje (V)
1.17	0.38	430	4
4.82	1.56	600	6
8.41	2.72	830	8
11.7	3.77	1100	10

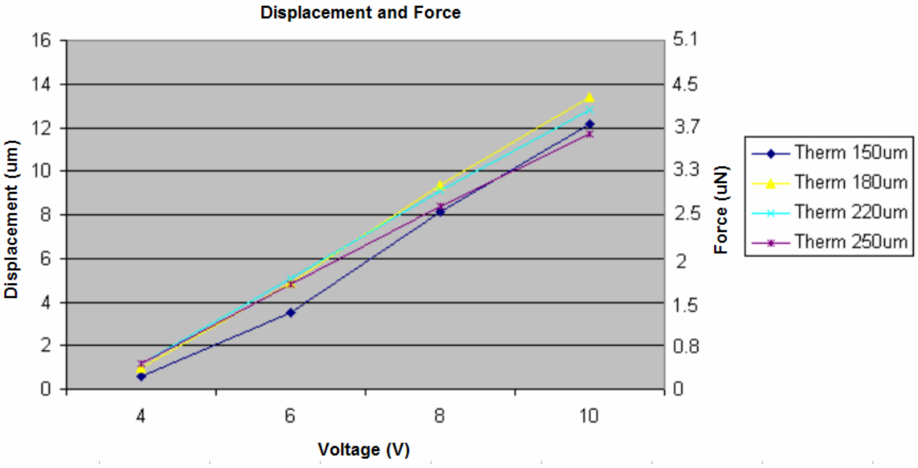


Fig. 12. Resulting graphs from Table 3**.**

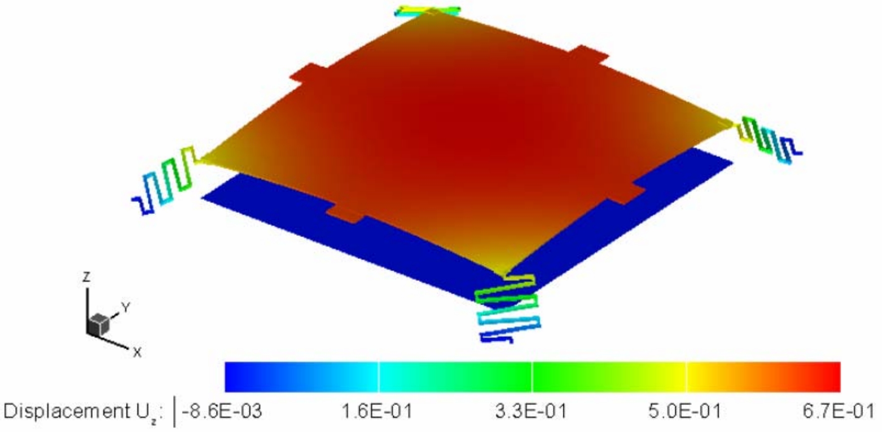


Fig. 13. FEA of plates' displacement using COVENTORWARE™.

5.2 Resulting Capacitance Variations

Figure 13 shows the displacement (with exaggeration factor over the Z axis) of one specific capacitor design showing 0.67 microns of displacement (added to the 2 microns initial separation between the plates, it gives 2.67 microns separation.) For this FEA, only one layer of PolySilicon was used (Poly1), and one can see that the upper plate bends a little from its corners, where the suspensions are attached. Therefore, we decided to use two Polysilicon layers in the design/manufacture of the upper plate, as discussed in section 4, to diminish this bending and increase the parallelism of the plates.

Figure 14 and Table 4 show the resulting displacements and calculated capacitance of the variable capacitors for different suspension systems and using the same applied force (4.41 µN.) Notice that we assumed the same displacements for different capacitor plates, since they are different only by nanometer scales, and contribute only to variations in femtoFarads in the final capacitances. The intention of results from Table 4 is to show that the capacitance variation (decrease in capacitance) that can be obtained from the suspension designs, using the maximum force applied (if using the 180 microns thermal actuator,) is shown on each element in the matrix from Table 4. The first row of this table represents the capacitance of the plates with no displacement of the upper plate (i.e., no applied force through the thermal actuators.) The second row represents the resulting displacement and corresponding capacitance calculations if plates were using the suspension with springs from the left side of Figure 9. The third row represents the resulting displacement and corresponding capacitance calculations if plates were using the suspension with springs from the center side of Figure 9, and the same for the fourth row, which used the right spring (from Figure 9) design in suspension systems.

Table 4 Resulting capacitance due to plate separation.

Capacitance (pF) for plate dimensions (L x L)			
distance (um) between plates	**L = 200um**	**L = 225um**	**L = 250um**
2.00	0.1770	0.2240	0.2766
2.33	0.1519	0.1923	0.2374
2.85	0.1242	0.1572	0.1941
3.71	0.0954	0.1208	0.1491

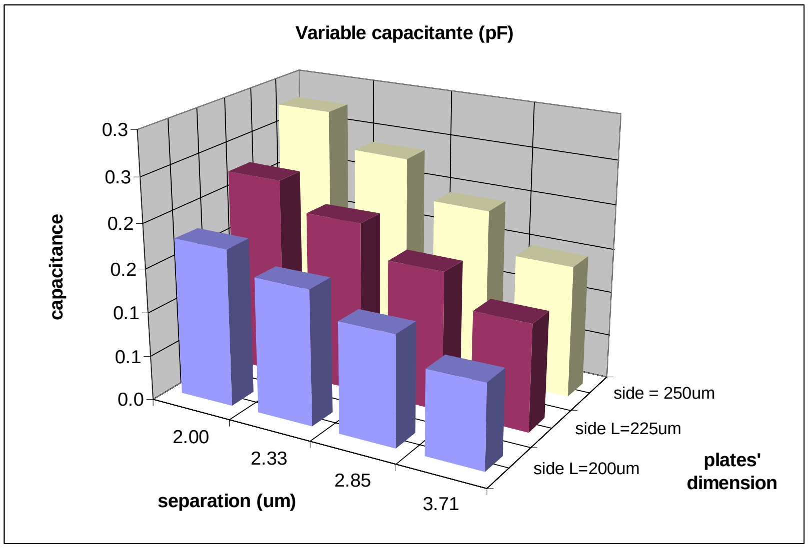


Fig. 14. Capacitance and displacement results while varying plate dimensions and suspensions' springs.

5.3 Resulting Fabricated Capacitors

Following the Design Rules of the process fabrication for PolyMUMPS™, we manage to fabricate the variable capacitors, as presented in probe station's picture shown in Figure 15.

6 Conclusions

The variable capacitor designed in this work used the PolyMUMPS™ process from MEMScAP™, and the designs consisted of two main components: 1) a set of squared plates composing the capacitor, where one plate is fixed to the substrate (Poly0) and the other is a moving square plate (composed of the Poly1 and Poly2 layers) having a mechanical suspension connected to the corners of it, and 2) a set of thermal actuators that push the moving plate away from the substrate. Depending on the electrical power applied on the thermal actuators, and due to the Joule's principle of operation, these would push up the variable plate from its sides, while the suspension pulls down the plate for the equilibrium.

Three different suspension systems were used to test the variation in capacitance. As expected, the more flexible springs used in the suspension system, the more capacitance variation obtained (due to the increment in plate separation between plates.)

Four different thermal actuator dimensions were used to calculate the pushing-up force of the upper capacitor plate. We found that for this type of thermal actuator, the 150 and 180 microns length in the hot arms provide the highest rate of force under an electronic power applied to the actuator (other variations would be the width of the arms.) The final design was sent for fabrication and properly fabricated as shown in Figure 15. No experimental measurements were possible to obtain since the parasitic levels in testing tips of the LCR meter were bigger than the capacitance of the designed capacitor. See the suggested work below related to further fabrication and measurements.

Further work will be developed as follows: 1) calculating the maximum voltage the capacitors can handle. This is, due that electrical DC bias voltage between plates creates an electrostatic force that attracts the upper plate down, we will investigate mitigating this electrostatic force with our pushing-up force with thermal actuators (contrary to approach suggested by [1];) 2) It is also required to evaluate the variation in capacitance, given application of AC signals in between the upper and lower plates; 3) we plan to fabricate the second plate with an extra layer of gold in the top, to facilitate the electrostatic voltage applied to it and mitigate the inductance reaction of the suspension springs; and 4) We plan to send for fabrication a bigger capacitor (upper and lower plates) but using the same actuators and springs designed in this work to be able to get reasonable measurements.

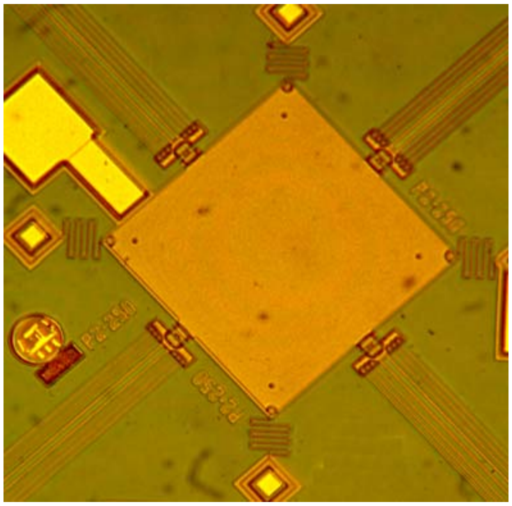


Fig. 15. Microscope view of a variable capacitor showing the thermal actuators and spring suspensions.

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