Optimization of a thermal actuator for low power/low cost applications

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Abstract: This work describes the study of a thermal actuator and modifications to the materials employed in order to decrease power consumption and implementation costs. For this study, we worked on improving the thermal actuator described in the work of T. Ebefors [1]. The criteria for choosing the new materials were lower power consumption, commercial availability, and ease processing. The idea behind the low power optimization is to find a material to improve thermal expansion at lower temperatures. For low cost optimization, the goal was to use an alternative to silicon-based approaches. Silicon fabrication facility was increase prototyping costs. The use of alternative materials will, therefore, make possible the implementations of applications and class prototypes at low cost for teaching purposes.

Keywords: thermal actuator, low power consumption, cost optimization.

1. Introduction

The main limitation of Latin-American universities to teach MEMS Technologies is the prototyping fabrication cost. Even though our university is member of academic consortia that make possible lower cost prototyping, the costs are still high, making impossible to finance MEMS fabrication for regular lab courses.

In addition to that, the time elapsed between tape out and delivery of the prototype is approximately 3 months. Scheduling makes the designing and measuring of a prototype difficult within one semester, which is the duration of lab courses.

For the reasons described above, the use of simulation software such as COMSOL Multiphysics makes possible the generation of robust design as well as the integration of knowledge from different disciplines, also offering a more realistic insight to the engineering design process. This is of great advantage to our students.

In comparison with other types of actuators, thermal actuators are capable of larger displacements at low operating voltages. However, power consumption is very high. For this reason, in our study we focused on a thermal actuator. The aim is to decrease its power consumption and at the same time, to simplify its fabrication process alone with the usage of commercially available materials. This will enable us to apply the actuators in lab projects and low cost applications.

We started the study by simulating the thermal actuator described by Ebefors [1] and modeled in COMSOL as an example of the Structural Mechanics Module [2], in order to determine its power consumption and displacement. The actuator consists of a thermally actuated joint with V-grooves in the base material at the joint region. The material filling the V-groove is heated and its thermal expansion causes a displacement of the actuator.

2. Use of COMSOL Multiphysics and Governing Equations

The thermal actuator shown in figure 1 was simulated using COMSOL Multiphysics with help of the Heat Transfer Module, COMSOL Multiphysics Module and the Structural Mechanics Module, to estimate the actuator’s total displacement, power consumption and maximum temperatures.

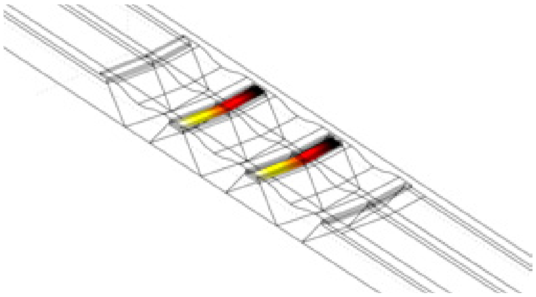

Figure 1. Thermal actuator showing the electric potential distribution in the resistive heaters. The yellow areas have the highest electric potential, while the black areas are grounded.

Heat in the structure is generated by resistive heating through the Joule effect, according to equation 1.

$$Q = \frac{1}{\sigma}\left|\vec{J}\right|^2 = \frac{1}{\sigma}\left|\sigma\vec{E}\right|^2 = \sigma\left|\nabla V\right|^2 \quad \textbf{(1)}$$

Where $\vec{J}$ represents the electric current density vector, $\vec{E}$ is the electric field vector, σ is the electric conductivity and ∇V is the electric potential gradient, which is applied as a boundary condition at the heating elements; applying the voltage during the first 10ms of a transient analysis with total analysis time of 20ms.

For each subdomain the heat source is active, causing a change in temperature as indicated by equation 2.

$$Q = \rho\, C_p \frac{\partial T}{\partial t} + \nabla \cdot \left(-k\nabla T\right) \quad \textbf{(2)}$$

Where ρ is the material density, C_p is the specific heat capacity at constant pressure. This temperature change is applied as a thermal load in the structural mechanics module, resulting in the deformation of the structure, according to equation 3.

$$\begin{gathered} \varepsilon_{total} = \varepsilon_{\sigma} + \varepsilon_{th} + \varepsilon_0 = \frac{\sigma}{E} + \varepsilon_{th} + \varepsilon_0 \\ \varepsilon_{th} = \alpha\left(T - T_{ref}\right) \end{gathered} \quad \textbf{(3)}$$

Where ε is the deformation, ε_0 represents the initial deformation, σ is the mechanical effort, *E* is the Young modulus and α is the linear coefficient of thermal expansion.

The thin conductive layers were simulated by means of shells. The heat transfer equation for a layer of thickness *d* is given by equation 4.

$$-\vec{n} \cdot \left(-k\nabla T\right) = -d\,\rho\, C_p \frac{\partial T}{\partial t} - \nabla \cdot \left(-dk\nabla T\right) \quad \textbf{(4)}$$

To determine the load capacity of the actuator, a pressure of 17.1 kPa was applied on a small area equivalent to a 20 mg mass, by means of a follower load, according to equation 5.

$$\vec{F}dA = -P\vec{n}da = -P\vec{n}\frac{da}{dA}dA \quad \textbf{(5)}$$

Where *P* is the continuous pressure, *da/dA* is the ratio of the deformed area to the area without deformation, and $\vec{n}$ is the vector normal to the surface.

We benefited from the versatility of COMSOL Multiphysics to evaluate different material options. Furthermore, the actuator was redesigned with help of a structural mechanics transient quasi-static analysis, associated with a heat transfer issue, thermal expansion and load analysis.

3. Simulations Results and Discussion

Since the material filling the V-groove was critical, we first proceeded to look for a replacement of the polyimide reported in [1]. Due to its large thermal expansion, low cost, availability, ease of processing and lower operating temperatures, we chose the Hytrel® 4056 thermoplastic elastometer from DuPont. By replacing the polyimide by Hytrel®, power consumption at maximum total displacement decreased by a factor of 3.7, while the actuator's displacement decreased almost 7% in relation to the original reference.

To decrease fabrication costs we proceeded to replace the actuator materials, as shown schematically in figure 2. Kapton® tapes and films as well as copper are commercially available at very low prices. Copper can be easily deposited on Kapton®. Furthermore, the heating resistors can be implemented by using commercially available wires.

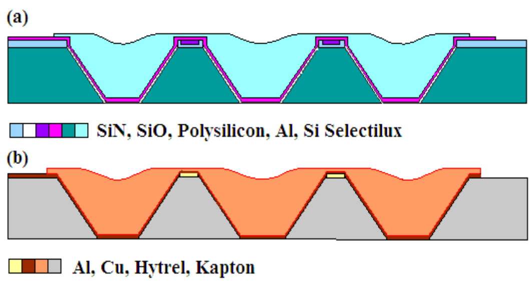

Figure 2. a) Original materials of the thermal actuator, b) Alternative materials for the low cost thermal actuator.

We initially carried out simulations with the original dimensions of the reference actuator [1], that is, 1mm x 30µm x 80µm. The configurations of the materials used in the actuators are summarized in Table 1.

Table 1: Materials used in the different configurations of the actuator.

Parts of the actuator	Reference	Replacement
Structural material	Silicon	Kapton®
Heating resistors	Polysilicon	Aluminum
Heat sink	Aluminum	Copper
Material filled in V-Grooves	Selectilux® HTR3-200	Hytrel® 4056

Simulation results for the configurations found in the references with the replacement materials for cases 1, 2 and 3, for t =10 ms are shown in table 2. Case 1 represents the actuator replacing only the V-grooves filling material, Case 2 represents the actuator replacing both the V-groove filling material and the structural material. Finally, Case 3 represents the actuator represents the actuator replacing the V-groove filling material, the structural material and the heat sink material.

For each simulation, we tried to obtain the same amount of displacement obtained by the reference actuator, to compare the temperature, voltage and power consumption required by the different configurations to achieve this displacement.

From table 2, it can be concluded that this substitution of materials leads to better performance, by decreasing the actuation voltage and the power consumption.

Table 2: Comparison of the results obtained for the different actuator configurations for t =10ms.

Variable/ Units	Reference	Case 1	Case 2	Case 3
Displacement [µm]	36.05	33.52	36.28	33.67
Temperature [ºC]	39.83	34.56	51.26	46.45
Voltage [mV]	30.0	21.0	16.5	16.5
Power consumption [mW]	20.67	5.56	3.81	3.29

The simulation results in table 3 are the equivalent to the maximum values of the displacement and temperature variables. The maximum value of the temperature should not be higher than 55°C to avoid changes in the physical behavior of Hytrel® 4056.

Table 3: Comparison of the maximum values obtained for the different actuator configurations.

Variable/ Units	Referen-ce	Case 1	Case 2	Case 3
Displacement [µm]	36.05	33.52	36.28	33.67
Temperature [ºC]	48.89	34.66	52.40	48.00

After observing the displacement and temperature ratio in table 3, as well as the displacement and power consumption summarized in table 2, we conclude that Case 3 presents the best performance; thus becoming our optimized actuator.

In order to develop a more complete analysis we conducted a transient analysis at 20 ms of both the reference and the case 3 configurations.

Figures 3, 4 and 5 show the transient analysis of the reference and optimized actuators. It also compares the total displacement, V-groove temperature and power consumption.

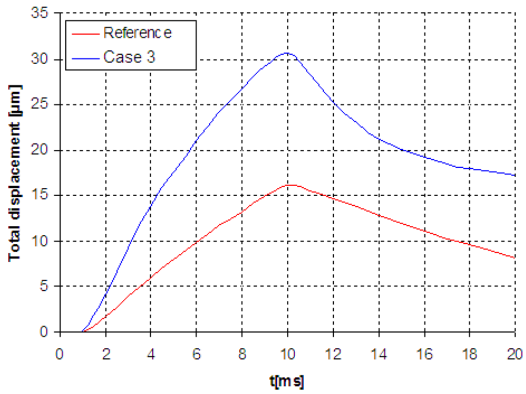

Figure 3. Total displacement vs time for the reference and optimized actuator.

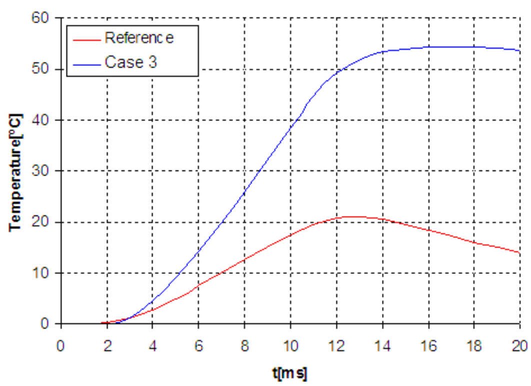

Figure 4. Temperature vs time for the reference and optimized actuator in the middle of the V-grooves.

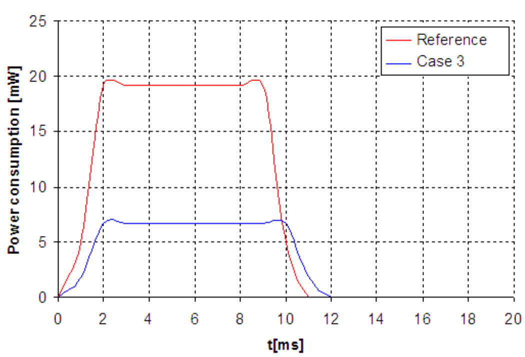

Figure 5. Power consumption vs time for the resistive heaters of the reference and optimized actuator.

Table 4 summarizes the final comparison of the reference actuator and the optimized actuator, at an actuation voltage of 20mV.

Table 4: Comparison between the actuator with original materials and the actuator with the optimized actuator (case 3).

Measurement	Reference	Replacement
Displacement [µm]	16.02	30.65
Temperature [ºC]	20.88	54.49
Voltage [mV]	20.0	20.0
Power consumption [mW]	19.14	6.82

The simulation results described in Table 4 show an improvement of 91.3% in the displacement, with a power consumption reduction of 64.4% when comparing the original actuator [1] with the optimized actuator.

Moreover, a larger scale actuator was simulated, with dimensions 1mm x 125µm x 400 µm and the material configurations indicated in Table 1, to obtain the actuator models at the scale required for their implementation in the lab courses.

It is also of interest to compare the displacement, temperature and power consumption of the larger scale optimized actuator when it operates in a bent configuration. Figure 6 and 7 show the temperature distribution and displacement of the actuator both in its straight (in-plane) and bent (out of plane) positions.

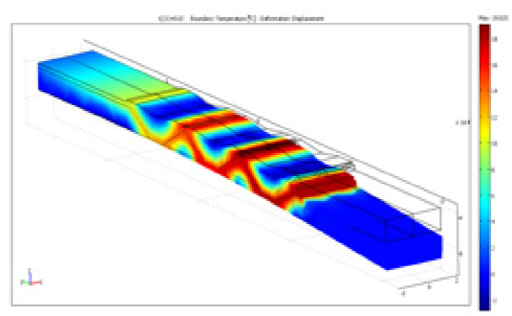

Figure 6. Temperature distribution and actuator displacement of the larger-scale, optimized actuator.

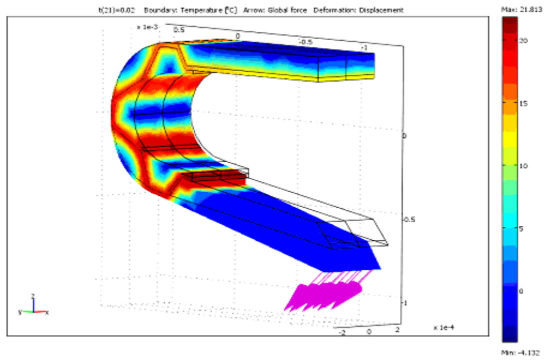

Figure 7. Temperature distribution and actuator displacement for the larger-scale, out of plane optimized actuator, 3D arrows show the force vectors applied.

Figures 8, 9 and 10 show the transient analysis of the out of plane, larger scale, optimized actuator, to determine total displacement, V-groove temperature and power consumption.

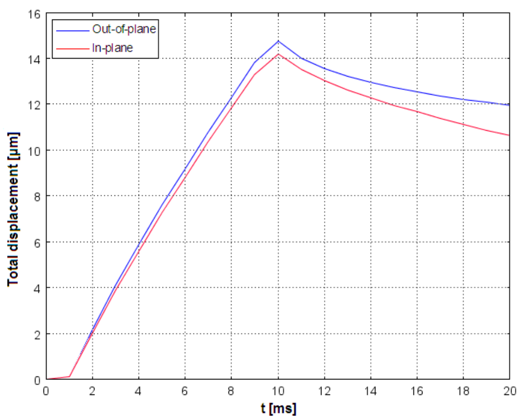

Figure 8. Total displacement vs time for the optimized out of plane actuator.

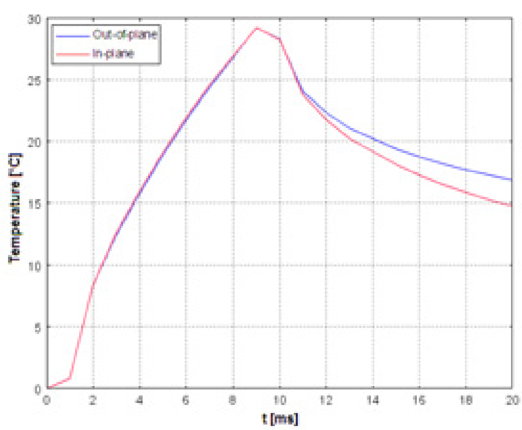

Figure 9. Temperature vs time for the optimized out of plane actuator.

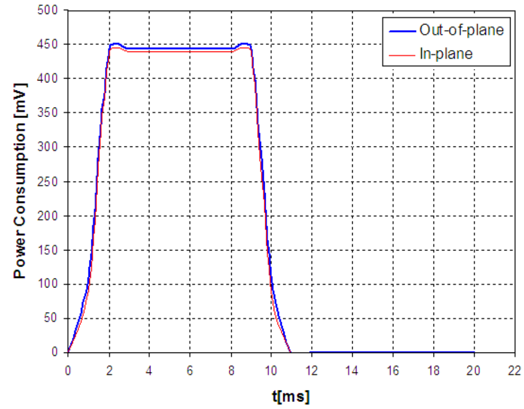

Figure 10. Power consumption vs time for the optimized out of plane actuator.

Table 5 presents the maximum values obtained for the straight and bent actuators, showing only a slight difference in displacement. The only important difference between them is shown in figures 8 and 9. Figure 8 shows that the in plane actuator returns to its initial position faster than the out of plane actuator. This is due to the slower cooling of the out of plane actuator, as shown in figure 9. Thus, the recovery time of the in plane actuator will be shorter, allowing it to be ready for a new actuation cycle.

Table 5: Comparison between the in-plane actuator with the out of plane actuator.

Measurements	**In-plane Actuator**	**Out of plane Actuator**
Displacement [µm]	14.17	14.74
Temperature [ºC]	29.20	29.18
Voltage [mV]	100	100
Power consumption [mW]	443.75	443.75

In order to determine if the out of plane actuator is able to withstand a 20mg load, a continuous force in the direction of the displacement was applied, that is, a follower load. This allowed verifying that, once the voltage source is turned off, the actuator cools down and returns to its initial position without plastic deformation.

A pressure of 17.1kPa must be applied to simulate a 20mg mass. Figure 11 shows the actuator displacement as a function of time with and without applied load.

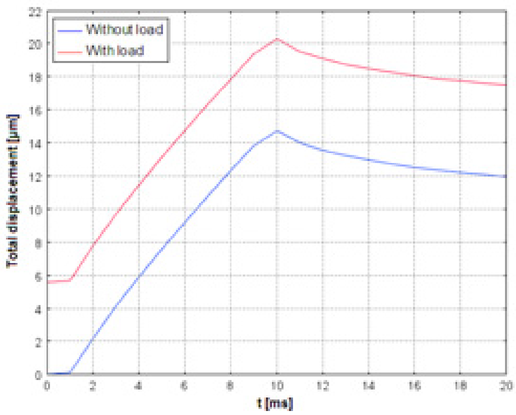

Figure 11. Total displacement of the out of plane actuator as a function of time with and without load.

Comparing the curves shown in figure 11, it is possible to observe a non constant increase of the displacement, due to the applied force. The change in displacement is 5.52µm. However, after 10 ms the displacement starts to decrease, which proofs that the actuator returns to its initial position even with the applied load.

5. Conclusions

It is possible to dramatically decrease the power consumption of the actuator with the new configuration of materials, that is, a reduction of 64% in power consumption, with displacement increase of 91%.

We obtained a low cost version of the actuator, which is easy to implement and thus can be useful for lab courses where students can implement the actuator themselves.

In addition to that, the out of plane actuator was simulated, showing that the only difference in comparison with the in plane actuator, is its slower time response to return to its initial position, due to a longer cooling time.

Incorporating actuator simulation with COMSOL Multiphysics in the lab course will help students integrate their knowledge of physics, system modeling and numerical methods in design projects, ultimately developing engineering design skills.

6. References

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