Perspectives of Thermo-electro-mechanical Micro actuators for micro switch Applications: Design and Simulation

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Abstract

In this work, thermo-mechanical simulations employing a 3D finite element analysis (FEA) of a current driven V-shaped actuator is presented. The structure's hot arms consist of polysilicon, which was used as the active material for deflection due to the joule effect. COMSOL 3.3 with stationary and parametric solvers was used to calculate the resulting deflection when current is applied. An analytical model in MATLAB was used to validate the results of COMSOL 3.3.

Keywords: Thermal actuation, MEMS, reliability, analytic modelling, finite analysis

Introduction

Thermo-electrical actuators are an attractive solution in the field of microsystems and micro technology due to their high deflection with small input current. Compared to electrostatic actuators [1][2], where high drive voltage is required, thermal actuators [3] are more compact. Moreover, the thermoelectric actuators are of interest, as their displacement and force are more important than for their electrostatic counterparts. Thermoelectric polysilicon-based actuators function in ranges of current and voltage compatible with traditional integrated CMOS electronics. All these advantages allow for use of the thermoelectric actuators in microphone-grips, micro-relays or engines step by step.

Currently, considerable experimental efforts are dedicated to improve the presented actuator's reliability. For this, it is necessary to control technological process steps and evaluate the performance of the used materials in real operating conditions. In order to have a better understanding of the electro-mechanical interactions involved and the actuator's thermomechanical behaviour, a 3D finite element analysis model has been introduced.

COMSOL Numerical Models

Figure 1 shows a schematic of the actuator. The actuator is made of polysilicon and anchored at both ends. The current is injected through metal electrodes deposited at the anchored ends. The two hot arms measure 100 µm in length, 4 µm in width and 0.5 µm in thickness. They are linked with a junction 4 µm wide, i.e. two times the width of each hot arm and form an angle $\theta = 7°$ with the horizontal axis. When current is applied, it causes the hot arms to heat and expand due to the joule effect; expansion is in opposite direction for the two arms, so the resulting force will move the junction upwards. As presented in figure 1, the actuation mechanism is based on the symmetric dilation of the arms.

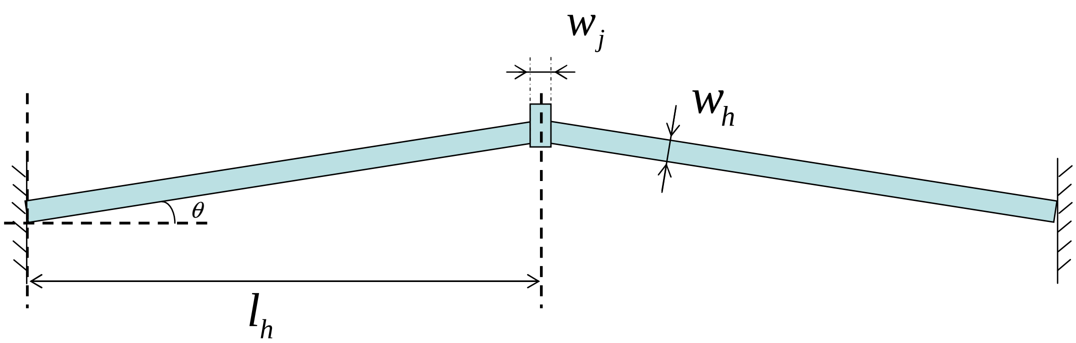

Figure 1: Schematic of the studied V-shape actuator.

For the needs of the simulation, the structure has been meshed using the free tetrahedral moving mesh (ALE). The meshed structure is shown in Fig. 2. There are x mesh nodes.

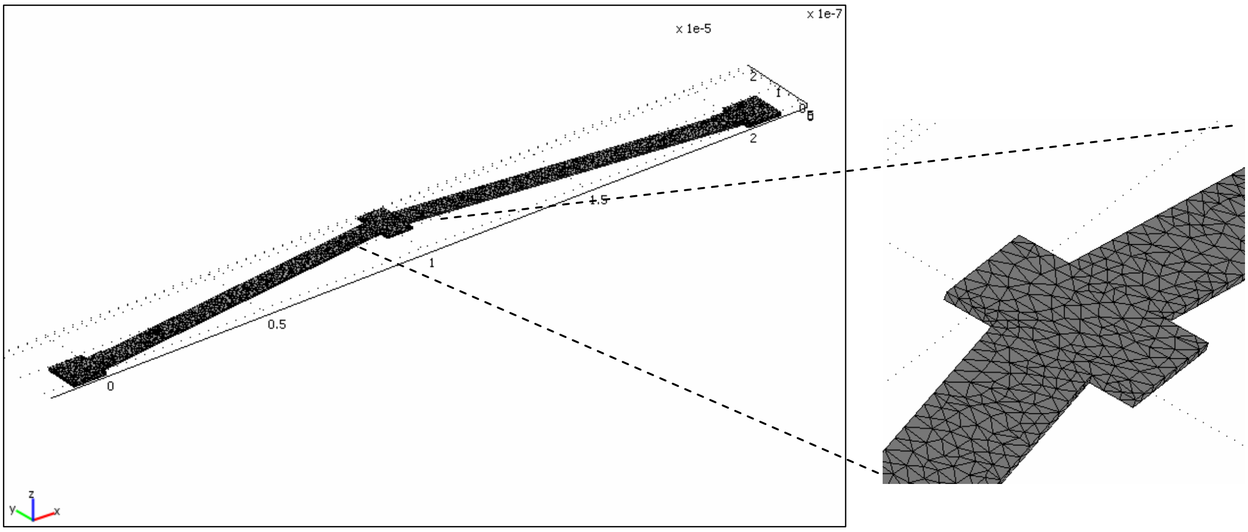

Figure 2: Meshing of the structure in COMSOL.

There are three types of boundary conditions: electrical, thermal and mechanical. The electrical boundary ones assume a constant current value of 3 mA applied at one of the fixed end, while the other fixed end is connected to ground. Electrical isolation is imposed to the whole structure. Concerning the thermal boundary conditions, both fixed ends assume 300 K and the whole structure is thermally isolated. The convection coefficient at the interface of air and polysilicon is 5. Finally, mechanical boundary conditions consist in fixing the anchored ends and leaving the rest of the structure free to move.

Results and Discussion:

a. Static analysis:

The simulation is done in two steps. In the first step, a thermo-electrical analysis is performed, so as to obtain the temperature distribution caused by the applied current. These results are then used in the second step (thermo-mechanical analysis) and we finally obtain the displacement as function of the applied current.

Electro-thermal modeling:

The Direct Spooles solver is used to calculate the voltage and temperature distribution as the current is applied through the resistive polysilicon film. In this solver, the set of equations is derived by the principle of electrical charge conservation (1) and total thermal energy (2) as presented below [4]:

- Conservation of electrical charges :

$$-\nabla \cdot (\sigma \nabla V - J^{e}) = 0 \quad (1)$$

- Equilibrium principle of thermal energy:

$$-\nabla \cdot (k(T)\nabla T) = \sigma(T)\left|\nabla V\right|^{2} \quad (2)$$

Where σ is the electrical conductivity, T is the temperature, V is the electrical potential, j^{e} the current density, k is thermal conductivity. The potential and temperature distributions obtained by the electro-thermal modeling of the actuator are shown below.

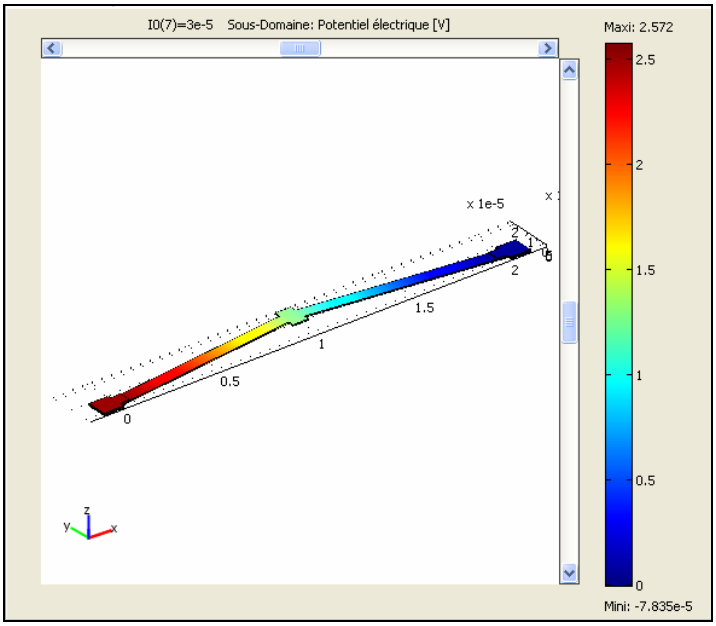

Figure 3: Distribution of the electric potential in the actuator.

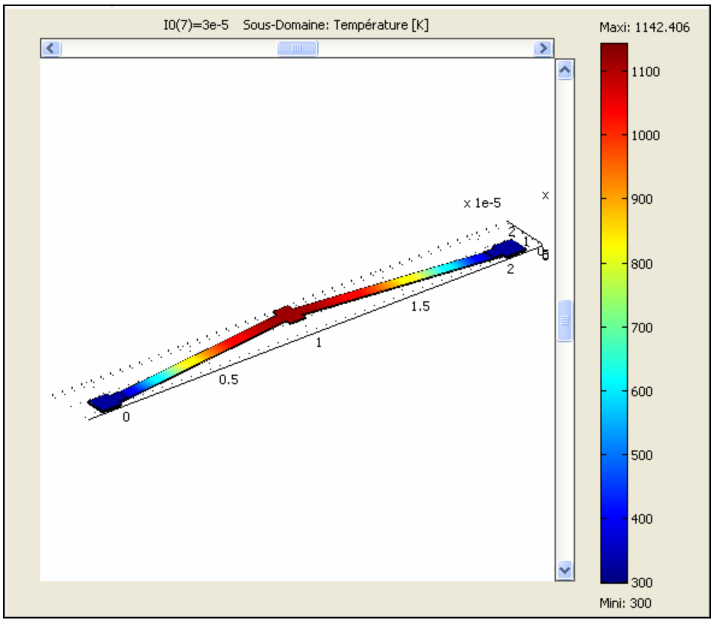

Figure 4: Distribution of the temperature in the actuator.

Thermo-mechanical modeling:

Based on the results of the previous "electro-thermal" modeling, the thermo-mechanical behaviour of the structure is modeled assuming both ends fixed. The solver addresses the resolution of the structural problem which consists in studying three vector fields, namely the displacement u(x), deformation ε(x) and stress σ(x), as well as their relationship. Figure 5 presents the relations among these quantities and the simulation results are shown in Figure 6.

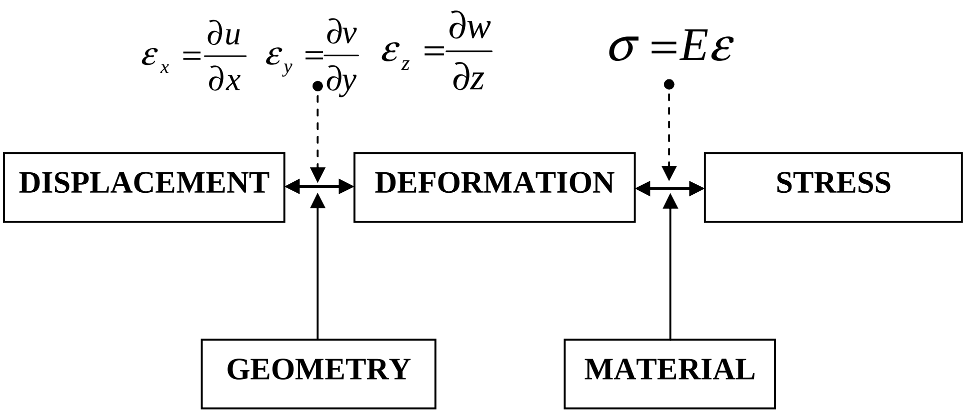

Figure 5: Relations among displacement, deformation and stress.

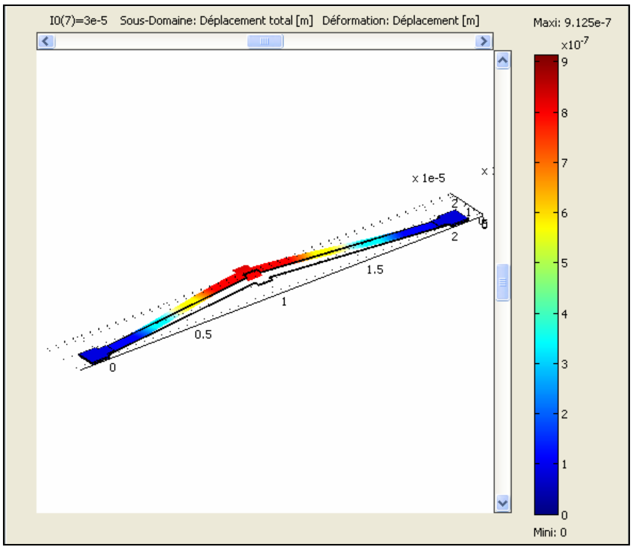

Figure 6: Deformation of the actuator.

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b. Parametric analysis:

To study the behavior of the actuator as a function of the current applied, parametric modeling is carried out. Current is varied in the range 0 to 30μA in 5μA steps. As current changes, both the displacement and temperature will change. The results of the parametric analysis are presented in Figures 7-9.

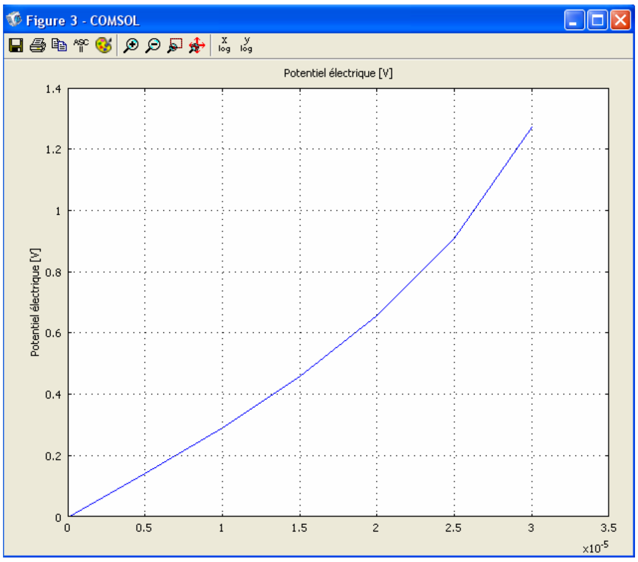

Figure 7: Variation of the potential as a function of the current applied.

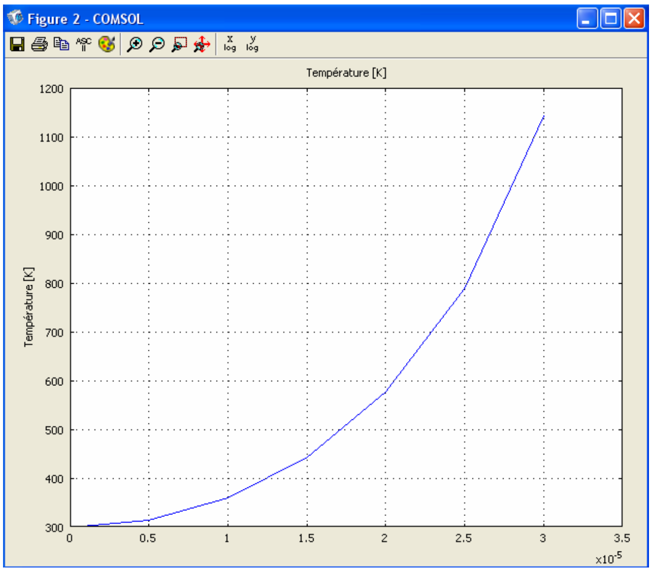

Figure 8: Variation of the temperature in the actuator as a function of the current applied.

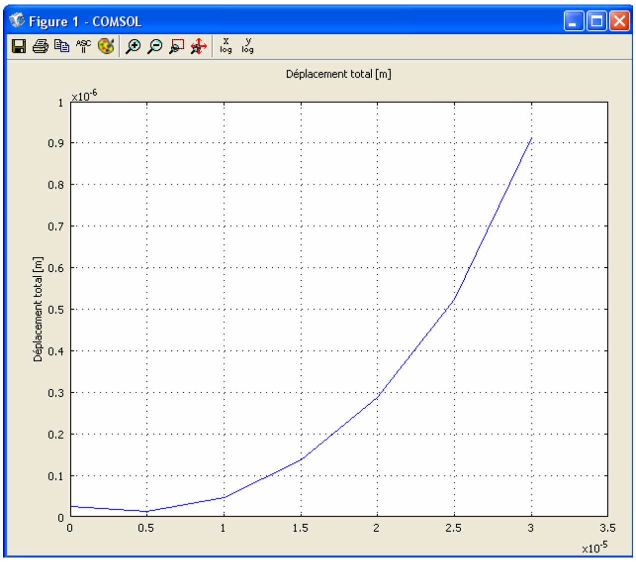

Figure 9: Variation of the displacement as a function of the current applied.

MATLAB analytical model:

The heat equation inside a unit cell of the structure is given by the following equation assuming stationary conditions [5]:

$$-k_p wh\left[\frac{dT}{dx}\right]_x + J^2 \rho wh\Delta x = -k_p wh\left[\frac{dT}{dx}\right]_{x+\Delta x} + F_S \Delta xw\frac{T - T_S}{R_T} \quad (3)$$

Where h is the thickness, x is the length, w is the width, k_p is the thermal conductivity of the polysilicon, J is the current density, F_S is the aspect ratio and R_T is the thermal resistance. The aspect ratio, F_S is inserted in order to take into account the thermal exchange with the surrounding air [6] and is defined by:

$$F_S = \frac{h}{w}\left(\frac{2t_v}{h}+1\right)+1 \tag{4}$$

The thermal resistance R_T, is between the substrate and the actuator. It depends on the thermal conductivities, k_v and k_n and the thicknesses t_v and t_n of the air and nitride layers respectively:

$$R_T = \frac{t_v}{k_v} + \frac{t_n}{k_n} \tag{5}$$

A second order differential equation is obtained by taking the limit of Δx --> 0 of the equation (3), which yields:

$$k_p \frac{d^2T}{dx^2} + J^2\rho = \frac{F_S}{h}\frac{T-T_S}{R_T} \tag{6}$$

Total losses in thermal energy per unit volume.
Total thermal energy generated by joule effect per unit volume.
Total losses of heat conduction per unit volume.

The solution of equation (6) allows us to find the temperature distribution of the hot arms and the junction:

$$\begin{cases} T_{h1}(x) = T_H + c_1 e^{m_h x} + c_2 e^{-m_h x} \\ \boldsymbol{T_j(x) = T_J + c_3 e^{m_j x} + c_4 e^{-m_j x}} \\ T_{h2}(x) = T_H + c_5 e^{m_h x} + c_6 e^{-m_h x} \end{cases} \tag{7}$$

Where C_i (with i=1 to 6) are the constants to be determined.

$$\begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ e^{m_h l_h} & \boldsymbol{e^{-m_h l_h}} & \boldsymbol{-e^{m_j l_h}} & \boldsymbol{-e^{-m_j l_h}} & 0 & 0 \\ \boldsymbol{m_h e^{m_h l_h}} & \boldsymbol{-m_h e^{-m_h l_h}} & \boldsymbol{-m_j e^{m_j l_h}} & \boldsymbol{m_j e^{-m_h l_h}} & 0 & 0 \\ 0 & 0 & e^{m_j(l_h+l_j)} & e^{-m_j(l_h+l_j)} & -e^{m_h(l_h+l_j)} & -e^{-m_h(l_h+l_j)} \\ 0 & 0 & m_j e^{m_j(l_h+l_j)} & -m_j e^{-m_j(l_h+l_j)} & -m_h e^{m_h(l_h+l_j)} & m_h e^{-m_h(l_h+l_j)} \\ 0 & 0 & 0 & 0 & e^{m_h(2l_h+l_j)} & e^{-m_h(2l_h+l_j)} \end{pmatrix} \begin{pmatrix} c1 \\ c2 \\ c3 \\ c4 \\ c5 \\ c6 \end{pmatrix} = \begin{pmatrix} T_s - T_{0h} \\ T_{0j} - T_{0h} \\ 0 \\ T_{0h} - T_{0j} \\ 0 \\ T_s - T_{0h} \end{pmatrix} \tag{8}$$

The solution of the above equation allows the determination of the constants C_i and as a consequence the temperature distributions along the hot arms of the actuator.
Therefore, T_{h1}, T_j and T_{h2} are the average temperatures in the first hot arm, the junction and the second arm respectively.

$$\overline{T_{h1}} = \frac{1}{l_h}\int_0^{l_h} T_{h1}(x)dx$$
$$\overline{T_j} = \frac{1}{w_j}\int_{l_h}^{l_h+w_j} T_j(x)dx \qquad (9)$$
$$\overline{T_{h2}} = \frac{1}{l_h}\int_{l_h+w_j}^{2l_h+w_{j_h}} T_{h2}(x)dx$$

This set of equations is solved using MATLAB. Figure 10 shows the results of the analytical modeling using MATLAB.

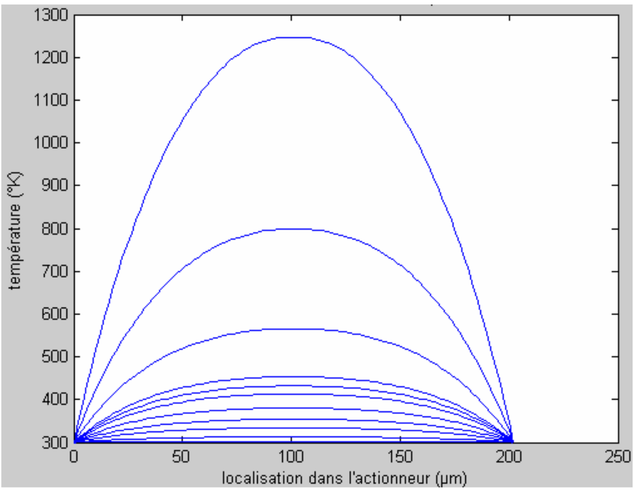

Figure 10: Temperature distribution for various values of the actuation current.

Conclusion :

The design and simulation of a V-shaped thermo-electric actuator are presented. The two independent simulation methods used (COMSOL, MATLAB) yield similar results; temperature is maximum in the central part of the actuator. The simulation shows that with increasing current, temperature and deflection also increase gradually. This increase is however limited, as high temperatures may cause plastic deformation and thus failure of the actuator. In this respect, simulations can help improve the actuator's reliability and lifetime, by determining a safe current and temperature operating range.

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