Design and Simulation of MEMS Based Thermally Actuated Positioning Systems

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Abstract: In this paper, we have addressed the design and simulation results of a thermally actuated positioning system that is capable of producing in-plane as well as out-of-plane displacements. The device was designed to be consistent with the design rules of PolyMUMPs process. The coupled multiphysics simulation and study of the electrical, thermal and - most importantly - the mechanical behavior of the positioning system was done using COMSOL Multiphysics. The device has an in-plane displacement range of 4.4 µm (2.2 µm in either direction). An out-of-plane displacement range of approximately 15 µm is achieved for an input voltage range of only 5V. The ability of precise control of movement of the positioning system in space is likely to lead to potential applications in diverse fields.

Keywords: Thermal Actuators, MEMS, Positioning Systems

1. Introduction

As silicon processing technology achieves higher levels of precision and control, a parallel advancement can be seen in the field of Micro Electro Mechanical Systems (MEMS). An important application of MEMS technology is in the field of micro or nano-scale positioning and manipulation systems. These have wide range of applications due to their small size, low cost, fast dynamics, and ease of integration with electronic devices and circuits. The need of high precision positioning systems has increased dramatically due to their crucial role in the fabrication of micro and nano-sized objects and assemblies. In addition, similar movements are required in controlled tilting and positioning of micromirror arrays in the field of adaptive optics. Traditional micro-fabrication techniques make it possible to generate arrays of MEMS positioning systems on a common substrate, which may be used for parallel manipulation tasks. Typical applications require controlled movements with range in micrometers with nanometer-scale accuracy, along all movement axes.

MEMS based actuators can be based on electrostatic, magnetic, piezoelectric or electro-thermal properties. We have chosen the thermal actuation mechanism as MEMS based thermal actuators are easier to fabricate compared to electrostatic or magnetic ones [1]. They can achieve higher deflections and generate high force output within an operating voltage that is compatible with modern IC circuitries. The limitations to these actuators come from their relatively high power consumption and low speed as the deflection depends on the heat transfer rates. The difficulty in achieving fast cool down rates typically limits their speed of operation to up to kHz order [2].

Several MEMS positioning stages, using different mechanical structures and actuation principles, have been investigated in this work. There is a large volume of work focused on devices producing only out-of-plane torsional motions for micromirror applications [3, 4]. While most existing positioning stages are capable of generating only in-plane (XY) translational motions, attempts to construct devices producing both in-plane (XY) and out-of-plane (Z) translational motions are fewer [5-7]. However, most of these devices have used piezoelectric actuation. Culpepper *et al.* have reported on design and fabrication of six-axis macro-scale nano-positioners using thermal actuation mechanisms [8]. A generic HexFlex compliant mechanism has been employed there to produce independent in-plane and out-of-plane displacements. But the device needs rather complex fabrication steps.

This paper presents the design and simulation results of a thermally actuated positioning stage that produces decoupled in-plane and out-of-plane motions of few micrometers at low actuation voltages. The device has been designed by maintaining the design rules given by PolyMUMPS: a three-layer poly-silicon surface

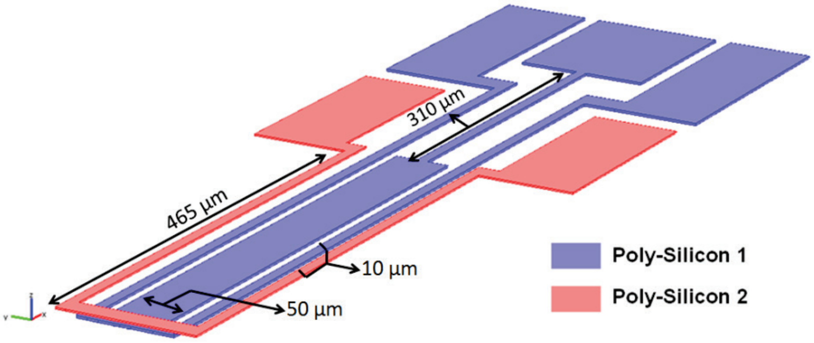

Figure 1. Designed actuator arm composed of double layer of poly-silicon, used to produce in-plane as well as out-of-plane displacement

micromachining process [9]. Hot arm, cold arm thermal actuators composed of single layer of poly-silicon (Poly1) are used to displace the center stage in the X and Y directions, and actuators composed of two layers of poly-silicon arms (Poly1 and Poly2) moves the center stage vertically. Finite element simulations of the device have been carried out using COMSOL Multiphysics software.

2. Design concept

The thermal actuators use resistive (Joule) heating to generate thermal expansion and movement. Both in-plane and out-of-plane displacement capabilities have been incorporated on the same structure using three layers (Poly0, Poly1, Poly2) of PolyMUMPs process, as shown in the Figure 1. For in-plane movement, bidirectional actuator made of single layer of poly-silicon (Poly1) is used. Poly-silicon via has been used to stack Poly 1 layer down to the substrate. This actuator is a modified form of conventional U-beam actuator. On both side of the common wide arm, a thin hot arm is attached. So when voltage is applied between a thin arm and the wide arm, that thin arm become 'hot' compared to the other thin arm and the wide arm acts as the 'cold' arm. So the 'hot' arm expands more and causes the device to bend. Due to symmetry, when voltage is applied between the other thin arm and the common wide arm, the device bends in the opposite direction. Lateral motion of the designed actuator is depicted in Figure 2. The advantage in using these W-shaped actuators for the positing system is that by selectively applying voltages among the actuators, the centre stage can be displaced laterally more compared to the conventional U-beam actuators, using a push-pull method.

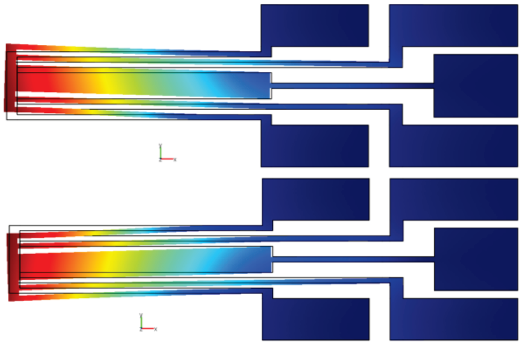

Figure 2. Bidirectional lateral movement of the actuator arm

For out-of-plane movement, double layer thermal actuator composed of two layers (Poly 2 and Poly 1) of poly-silicon is employed. Here also poly-silicon via has been used to stack Poly 2 layer down to the Poly 1 layer. When current is passed through the top poly-silicon layer (Poly 2), it bends more as it gets more heated compared to the bottom poly-silicon Layer (Poly 1). Thus, the actuator moves vertically downward. It is shown on Figure 3. In a similar manner, we can displace the positioning stage vertically upward by heating the bottom layer.

In the complete positioning system, we have incorporated the features for both in-plane and out-of-plane motion. Consequently, four such actuator arms are attached to the central positioning stage via flexural springs, which are capable of both in-plane and out-of-plane motion, in order to obtain displacements in all possible directions independently.

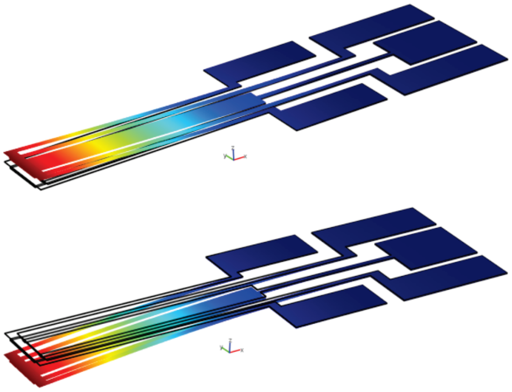

Figure 3. Upward and downward motion of the actuator arm

As shown in Figure 4, the thermally actuated positioning system is symmetrically designed. The central stage is a 250 µm square and made on the upper poly-silicon (Poly 2) layer. The thickness of the Poly 1 and Poly 2 layers are 2 and 1.5 µms respectively. The design is consistent with the design rules of the "Polysilicon Multi-user MEMS Process" (PolyMUMPs) process.

3. Finite Element Analysis using COMSOL Multiphysics

In order to analyze the static behavior of the positioning system, COMSOL Multiphysics FEM software is used. The coupled multiphysics simulation and study of the electrical, thermal and most importantly, the mechanical behavior of the device is done using thermal-electric-structural interaction mode of COMSOL Multiphysics MEMS module.

Poly-silicon was used as structural material and air was defined for the heat convection to the surrounding volume in the model. Different material properties have been defined in Table I.

For simulations of the designed positioning system, the ends of the actuators, which are in contact with the substrate (electrical contacts), are mechanically fixed. All other boundaries are kept free to move.

In thermal boundary conditions, the surfaces attached to the substrate are kept at the constant substrate temperature (300K), modeling an infinite heat sinks.

Since all other boundaries interact thermally with the surroundings by conduction through thin layers of air, the major part of heat transport occurs through the contacts made on to the Silicon substrate which therefore acts as the sink of generated heat. Secondly, heat release from the surfaces is modeled linearly using a lumped co-efficient which will model the removal of heat from the air exposed surface as a function of temperature is taken here. The heat transfer due to convection (and/or conduction) as a function of temperature is

$$q(T) = h(T - T_0) \qquad (1)$$

Where h is the heat transfer co-efficient of the material, which represents the removal of constant power for every degree Kelvin, on the form of heat per unit area. The linearity of (1) is not exact but a good approximation.

There are three mechanisms of heat flow: conduction, convection and radiation. According to literature [10], the heat dissipation through radiation to the ambient can be neglected in comparison with the heat losses through conduction to the anchors which are considered as heat sinks and the heat losses through air to the substrate due to convection.

For in-plane displacement of the positioning system, DC voltages have been applied selectively to the end of the arms (contact pads) of the four bottom poly-silicon actuators. For downward movement, voltages have been applied across the upper poly-silicon layer (Poly 2). When voltage is applied, the upper layer warms up compared to the bottom layer, due to resistive Joule heating and thus bends downward. Similarly, for upward movement, voltage has been applied across the outer thinner arms of the bottom poly-silicon actuator layer (Poly 1).

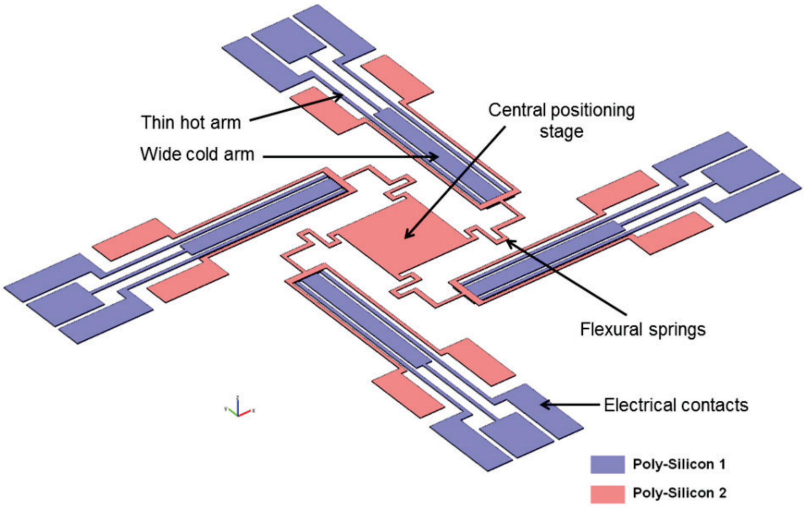

Figure 4. Designed positioning system

4. Results and Discussion

The applied voltage range for the actuators is kept at a low value which is compatible with normal IC circuitry. This is a typical advantage of the thermal actuation mechanism. For in-plane and out-of-plane actuations, the displacement produced and the maximum temperature generated are investigated. The key factor that limits the performance of a thermally actuated device is temperature. As reported in [11], that the temperature of a poly-silicon device should be kept under 1200K to avoid thermal failure, so analysis is done by keeping the maximum temperature well below that value.

Figure 4 shows the simulation results of the in-plane movement of central positioning stage. As shown in Figure 5(a), to move the stage along the x-axis, voltage has been applied to the left and right actuators. In this particular case, the left actuator “pulls” the central stage in the negative x-axis direction, while, the right actuator “pushes” it in the same direction. In a way, it can be said that the device moves laterally using a push-pull method. Similarly for y-movement, top and bottom actuators can be actuated. Furthermore, as shown in the Figure 5(b) voltage can be applied to all the four actuators to move the positioning system diagonally. It may happen that during in-plane actuation, some offset vertical displacement is produced. But it can be nullified by suitably actuating the upper poly-silicon layer. The variation of the in-plane displacement with voltage is plotted on the Figure 6. As shown, displacement increases non-linearly with voltage. The maximum displacement achieved is 2.2 µm with 12V applied voltage. Since the positioning system shows bidirectional motion due to the use of W-shaped in-plane actuators, so it can move up to a total distance of 4.4 µm along x- or y-directions.

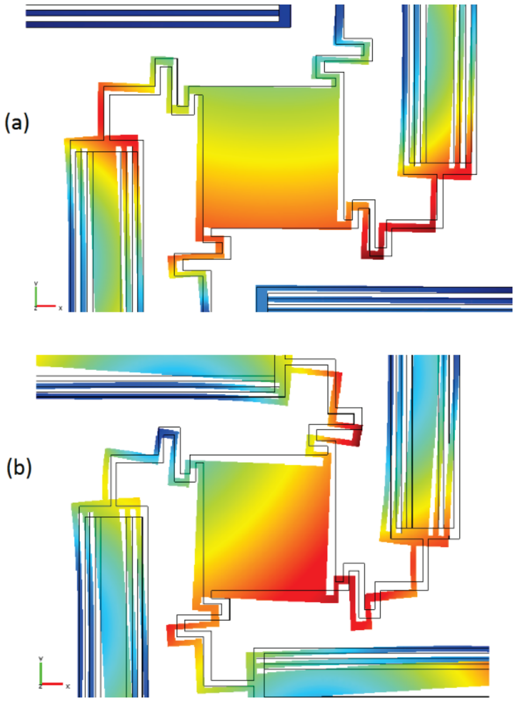

Figure 5. In-plane displacement of the central stage. (a) along x-direction and (b) along diagonal.

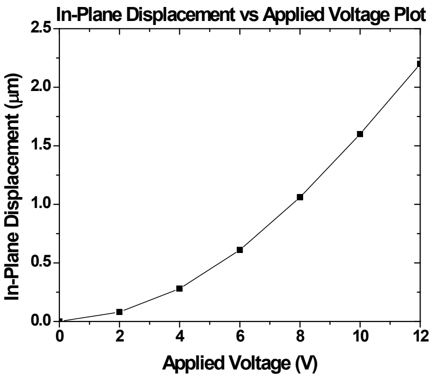

Figure 6. Variation of in-plane displacement with applied voltage

Figure 7 shows the simulation results of the out-of-plane movement of the positioning system. As shown in Figure 7(a), voltage can be applied to the top poly-silicon layers of all the four actuator arms in order to produce a vertically downward movement of the system. Also, by applying voltage to the upper layer of only one actuator arm, tilting of the central positioning stage can be achieved. This is depicted in Figure 7(b). Thus, the versatility of the designed device is increased. The variation of the out-of-plane displacement with voltage is plotted on the Figure 8. It can be seen that, deflection increases in a non-linear manner with voltage. The simulated structure is capable of producing large out-of-plane displacement (~7.5 µm) with a small applied voltage of 5V.

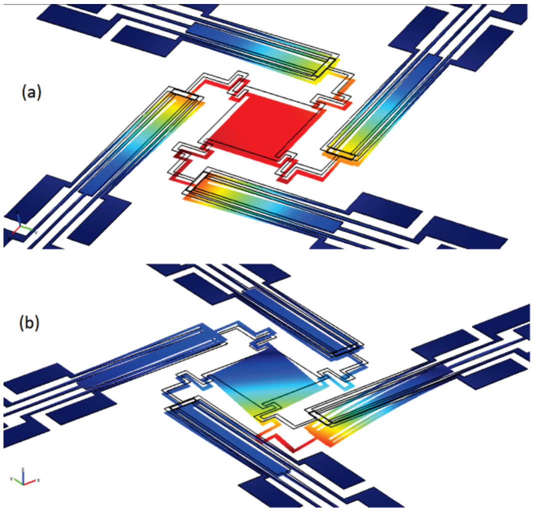

Figure 7. Out-of-plane displacement of the central stage. (a) along downward direction and (b) tilting motion

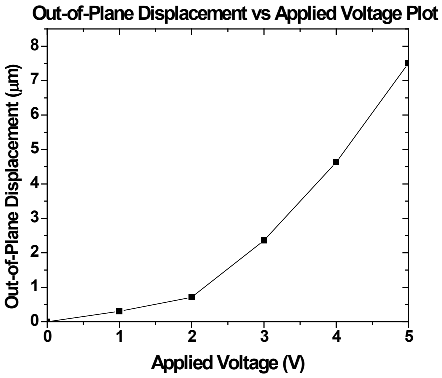

Figure 8. Variation of out-of-plane displacement with applied voltage.

In case of in-plane actuation, maximum temperature is generated in the thin end of the wide poly-silicon arm. For 12V of applied voltage, the maximum temperature generated is 845K, which is well below the maximum allowable value. For out-of-plane actuation, maximum temperature is generated on the thin hot arms of the respective poly-silicon layer depending upon the mode of actuation. For 5V input voltage, a maximum temperature of 362K is generated, which is very small. The variation of temperature in poly-silicon is shown in Figure 9. It can be seen that, temperature varies in a non-linear manner with applied voltage.

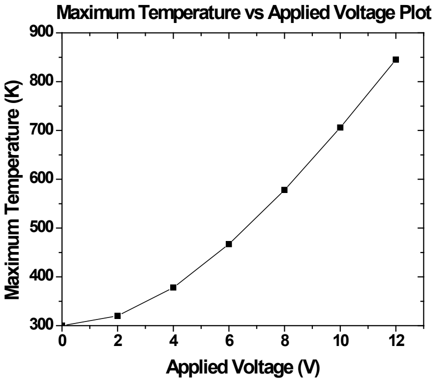

Figure 8. Variation of temperature with applied voltage.

5. Dynamic Response of the Actuators

Dynamic response of MEMS devices is often determined experimentally and then compared to its analytical model due to complexity of the problem. Even transient modeling using FEM simulators is also a tough task because of the large number of nodes in the three dimensional structural model [12].

Though we can estimate the transient performance of the device based on the principles of heat transfer. As reported by Varona et al [12], the cooling transient of the structure, assuming that it is getting convectively cooled, is given by:

$$T(t) = T_a + (T_i - T_a)e^{-t/\tau} \qquad (2)$$

Where T_a is ambient temperature and T_i is the initial temperature at t=0, $\tau = \left({\rho c V}/{hA}\right)$ is the time constant (h is the average convection coefficient over the surface, A is the cross-sectional area, ρ is the density of the material, V is the volume, c is the specific heat capacity of the material).

Thermal conductivity is not considered in the above equations as it is not important in the cooling process. As the thickness of the polysilicon arms are small compared to the length, we can assume that temperature is uniform along the thickness of the arms and so internal conduction is not important.

The analogous dependence can be expressed for heating transient behavior when the heat is transferred by conduction. The analytical solution for heating transient is defined by:

$$\mathrm{T(t)} = \mathrm{qAR_t}(1 - \mathrm{e}^{-\mathrm{t}/\tau}) \qquad (3)$$

Where Rt and τ are the thermal resistance and the time constant respectively described by

$$\mathrm{R_t} = [\frac{\mathrm{t_v}}{\mathrm{k_v}} + \frac{\mathrm{t_n}}{\mathrm{k_n}}] \text{ and } \tau = \frac{\rho \mathrm{cV}}{\mathrm{hkA}}(\mathrm{hLt} + \mathrm{k})$$

In the above expression t_v is the thickness of the air layer, t_n is the thickness of the silicon-nitride layer and *h* is the thickness of the hot-beam of the actuator. k_v and k_n are the thermal conductivity of the air and the nitride layer respectively.

Figure 9 illustrates the total time response of the actuator composed by the time required for heating and cooling. The response time is of the order of milliseconds. So we can approximately say that the positioning system can be driven at frequencies of the order of kHz, which is in agreement with literature [2], as we mentioned before.

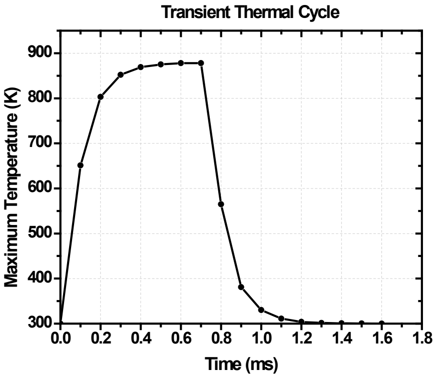

Figure 9. Estimated transient response of the poly-silicon actuator

6. Conclusions

In this paper, we have discussed the design and behavioral simulations of MEMS based thermally actuated positioning system that is capable of producing both in-plane and out-of-plane movements independently. The design has been made by following the rules of PolyMUMPs process. Finite element based simulations have been done using COMSOL Multiphysics software to model the performance of the system. It is seen that the positioning stage can move up to 4.4 μm (2.2 μm in either direction) along x- or y- directions. During out-of-plane operation, 15 μm of displacement range (7.5 μm in either direction of z-axis) has been achieved for an input voltage up to only 5V. The important factors for design of any positioning system are range, resolution and bandwidths. For the designed device, micrometer range of motion range has been obtained with hundreds of nanometers of resolution for increment of a single volt, both for in-plane and out-of-plane movements. The speed of operation of thermally actuated devices is however limited by slow thermal response. The temperature generated due to Joule heating is also within the allowable range.

7. Acknowledgements

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8. References

1. J Singh and J H S Teo, Two axes scanning SOI MEMS micromirror for endoscopic bioimaging, Journal of Micromechanics and Microengineering, 18(2008) 025001 on 11 Dec 2007.
2. Comtois and Bright, Applications for surface-micromachined polysilicon thermal actuators and arrays, *Sensors Actuators A*, **58**, 97-98 (97).
3. U Krishnamoorthy, D Lee and O Solgaard, Self-aligned vertical electrostatic combdrives for micromirror actuation J. Microelectromech. Syst., **12**, 458–64(2003).
4. J Kim and L W Lin, Electrostatic scanning micromirrors using localized plastic deformation of silicon J. Micromech. Microeng., 15, 1777–85(2005).
5. L Fan, M C Wu, K D Choquette and M HCrawford, Self-assembled microactuated XYZ stage for optical scanning and alignment Proc. Int. Conf. Solid-State Sensors and Actuators (Chicago, IL) pp 319–22(1997).
6. Y Ando, Development of three-dimentional electrostatic stages for scanning probe microscope Sensors Actuators A 114, 285–91(2004).
7. K Takahashi, M Mita, H Fujita and H Toshiyoshi, Topological layer switch technique for monolithically integrated electrostatic XYZ-stage Proc. IEEE MEMS (Kobe, Japan) pp 651–4.
8. M L Culpepper and S C Chen, Compliant mechanisms for micro-scale spatial manipulators: applications in nanomanipulation, patent pending.
9. Jim Carter, Allen Cowen et al, PolyMUMPs Design Handbook (a MUMPs® process),MEMSCAP.
10. Q A Huang and N K S Lee, Analytical modeling and optimization for a laterally-driven polysilicon, Microsyst. Tech., **5**, 133-7(1999).
11. R Venditti, J S H Lee, Y Sun and D Li, An in-plane, bi-directional electrothermal MEMS actuator, Journal of Micromechanics and Microengineering, **16**, 2067-2070 (2006).
12. Varona, Hamoui et al, Modeling of MEMS Thermal Actuation with External Heat Source, *Fourth Congress of Electronics, Robotics and Automotive Mechanics*, 591-596(2007).

9. Appendix

Table 1: Physical and Material parameters used in FEM simulation

Parameters	Value	Unit
Young Modulus of polysilicon	162	GPa
Poisson ratio of polysilicon	0.22	
Electrical resitivity of polysilicon	20	Ω.µm
Thermal conductivity of Polysilicon	34	W/m.K
Temperature coefficient of resistivity of polysilicon	$0.7 \text{ X } 10^{-3}$	1/K
Thermal conductivity of air	0.04	W/m.K