MEMS Based Modeling And Simulation Of An Electrically And Thermally Actuated MICRO-Aligning Arrangement

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Abstract - *In this paper, a newly modeled 3-D MEMS electrothermally actuated positioning cum aligning arrangement has been designed and simulated using COMSOL 4.3b based on finite element method (FEM). Electrothermal mechanism is the most widely used mechanism for providing large displacements at very small voltages. Most significant prerequisites for the actuators in a microaligning system include accuracy, range of displacement, degrees-of-freedom. Two types of electro-thermal actuation mechanisms are used in the designed micro-device. For in-plane movement poly-silicon made hot arm, cold arm actuator is used. For out-of-plane movement, difference in the resistivity of two different materials aluminium and titanium used in microactuators has been manipulated. In the complete alignment structure, four in-plane and four out-of-plane microactuators are attached to the central microaligning platform to obtain displacements in all possible directions independently. The simulated design is capable of producing decent range of displacement in all possible directions using very small voltages. The range of motion is in the micron order, while the resolution is of the order of nanometer scale. The ability of precise control of deflection of the microaligning system in space is likely to lead to potential applications in various fields.*

***Key Words*: Actuator, Sensor, Microgripper, COMSOL, electrothermal, Polysilicon**

1 INTRODUCTION

Recently, with the increasing effort to reduce the system size and products in the industries, the need for micro as well as nanotechnology has become an important issue. An important application of MEMS technology is in the field of micro or nano-scale micro-alignment 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. In addition, similar movements are required in controlled tilting and aligning of micromirror arrays in the field of adaptive optics. MEMS based actuators can be based on electrostatic, magnetic, piezoelectric or electro-thermal properties. We have chosen the electrical as well as thermal actuation mechanism as MEMS based electrothermal actuators are easier to fabricate compared to electrostatic or magnetic ones. These can achieve higher deflections and generate high force output within an operating voltage that is compatible with modern IC circuitries. While most existing micro-positioning stages are capable of generating only in-plane (x-y) translational motions, attempts to construct devices producing both in-plane (x-y) and out-of-plane (z) translational motions are fewer. However, most of these devices have used piezoelectric actuation In my work W-beam micro actuators- alpha and beta have been employed for assembling the micro aligning cum positioning arrangement.Here this study presents the design and simulation results of a electrically and thermally actuated aligning cum positioning platform that produces decoupled in-plane and out-of-plane motions several micrometers at low actuation voltages. The device has been designed by maintaining the design rules given by polymumps: a three-layer poly-silicon surface-micromachining process. Finite element simulations of the device have been carried out using COMSOL Multiphysics 4.4 software.

2 ELECTROTHERMAL ACTUATION

Electrothermal microactuators have promising future in MEMS applications due to their capabilities of generating larger deflections at low voltages and their implementation is easier Its operational principle is based on thermal expansion by non-uniform Joule heating and thus deflection is produced [3,5]. Thermal actuation is based on the following principles.

2.1 Thermal Expansion

The nature of heat is in vibration of atoms and electrons making material. The more an atom is vibrating, the more it is hot and will excite atoms around it. Now consider all atoms from a material are strongly vibrating and have tendency to push each other way to get enough place as their vibration amplitude is larger. This means that whole part will get bigger. This is called thermal expansion. Consider a material of length L at a constant reference initial temperature T. If the temperature of the material is changed by an amount ΔT from the reference value, the change in length ΔL of the material is predicted by the equation [4,7]

$$\Delta L \propto L\Delta T \qquad (1)$$

where coefficient of thermal expansion depends upon the material and temperature.

2.2 Coefficient of thermal expansion

Several types of coefficients have been developed; volumetric, area, and linear which is used depending on the particular application and which dimensions are considered important. For solids, one might only be concerned with the change along a length, or over some area. The volumetric thermal expansion coefficient is the most basic thermal expansion coefficient. In general, substances expand or contract when their temperature changes, with expansion or contraction occurring in all directions. Substances that expand at the same rate in every direction are called isotropic. For isotropic materials, the area and linear coefficients may be calculated from the volumetric coefficient. Mathematical definitions of these coefficients are defined below for solids, liquids, and gases.

2.3 General volumetric thermal expansion coefficient.

In the general case of a gas, liquid, or solid, the volumetric coefficient of thermal expansion is given by

$$\alpha_V = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p \quad (2)$$

The subscript p indicates that the pressure is held constant during the expansion, and the subscript "V" stresses that it is the volumetric (not linear) expansion that enters this general definition. In the case of a gas, the fact that the pressure is held constant is important, because the volume of a gas will vary appreciably with pressure as well as temperature. For a gas of low density this can be seen from the ideal gas law.

2.4 Expansion in solids.

Materials generally change their size when subjected to a temperature change while the pressure is held constant. In the special case of solid materials, the pressure does not appreciably affect the size of an object, and so, for solids, it's usually not necessary to specify that the pressure be held constant. Common engineering solids usually have coefficients of thermal expansion that do not vary significantly over the range of temperatures where they are designed to be used, so where extremely high accuracy is not required, practical calculations can be based on a constant, average, value of the coefficient of expansion.

2.5 Expansion in mixtures and alloys.

The expansivity of the components of the mixture can cancel each other like in invar. The thermal expansivity of a mixture from the expansivities of the pure components and their excess expansivities follow from:

$$\frac{\partial V}{\partial T} = \sum_i \frac{\partial V_i}{\partial T} + \sum_i \frac{\partial V_i^E}{\partial T} \quad (3)$$

3 RESISTANCE AND RESISTIVITY.

We have the following equation of resistance:

$$R = \rho L / A \quad (4)$$

This is the relation between the resistance and the resistivity. The resistivity is the property of the material and the resistance is the property of the object. The resistivity of the most materials is linear with temperature as the following equation:

$$\rho = \rho_o[1+\alpha_r(T - T_o)] \quad (5)$$

where ρ_0 is the resistivity at the temperature T_0. $\propto_r$ is the resistivity temperature coefficient. [4,7]

4 JOULE HEATING.

The power loss (rate of energy loss per unit time) in a resistor appears in the form of thermal energy and is given by

$$P = VI = I^2 R \quad (6)$$

This power loss is also known as ohmic heating, Joule heating, or I^2 R loss. For the same resistivity and a given length, members with smaller cross-sectional area will have higher resistance. This difference in cross sectional area allows for different expansion rates for different parts of MEMS devices made of a single material. For a given current input, the smaller cross sectional area member will have a higher resistance, greater increase in temperature and elongate more than other members with the same length due to greater ohmic heating [4].

5 THERMAL ACTUATION IN ACTUATOR.

If a current flowing through a structure meets different resistivity levels, the heating calculated with Joule's law will be higher where resistance is higher. So, structures with different widths (same material) make different resistivity levels. Two beams of same material but different widths, make the structure with different resistance. Thus different amount of heat will flow through them according to Equation (6). The U-beam actuator consists of three resistive parts with two long paths of different widths and one short path linking them .

The only requirement with this structure to achieve motion is to have one arm expand more than the other [2]. Involving flexure arm in the actuator design is an important design parameter. Better deflection performance is achieved by thinner flex arm. Flexure converts more of the force generated by the hot arm into motion of the actuator tip.

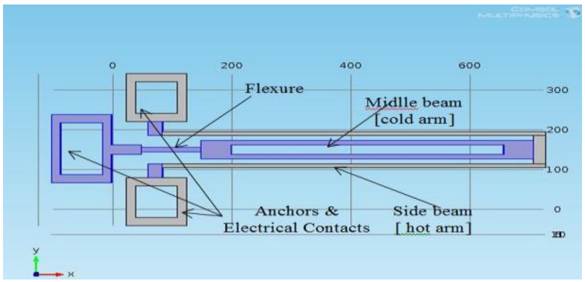


Fig-1: Actuator Design

If the flexure arm is too long, then it may expand more than the thin arm and oppose the desired actuator movement. Thus, this flexure helps the narrow arm to get more deflected. If current flows through the above structure, current will flow through these arms with approximately same heat distribution. As one path is thinner than the other, the thinner path will become more hotter than the other due to lesser resistance. So, its expansion will be higher. The result is thinner part create mechanical force pushing structure in direction thinner to wider arm. This is an amplification of thermal expansion, enough to be used for thermal actuator design [3,4].

6 DESIGN OF MICRO-ALIGNING ARRANGEMENT

Here W- beam actuator is used in four pronged structure of micro-alignment cum positioning arrangement. 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 work planes. For in-plane movement, bidirectional actuator made of two layers of aluminium, titanium and poly-silicon.

For out-of-plane movement, double layer electrothermal actuator composed of two layers of poly-silicon and aluminium is employed. When current is passed through all four micro actuators, structure bends in the same direction on all sides and the aligning arrangement moves vertically downwards.

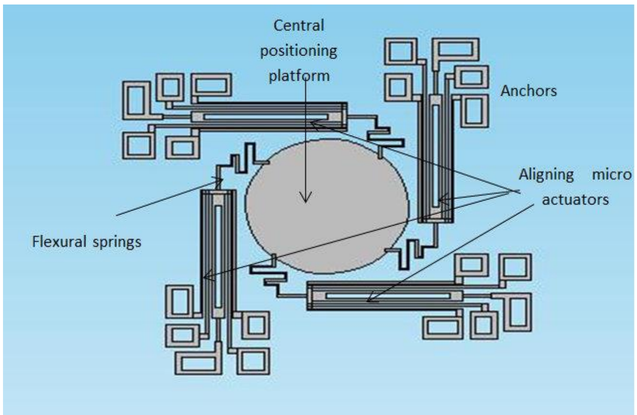


Fig - 2: Design Of Micro Aligning Cum Positioning Arrangement

This arrangement works on the principle of W- beam micro actuator design. The structure here consists of hot arms, cold arms, anchors and a flexural spring joining the four microactuators to the central positioning platform. The positioning platform is originally at different level, so a bar like structure of dimensions **27 µm x15 µm x 7 µm** is used on the tips of flexural springs to form the connectivity. The cold arms and the base are carved or etched out to reduce the bulkiness in the system Flexures join the cold arms to the anchor or base, while a Polysilicon strip at the tip of micro-actuator form a joint between cold arm and hot arm [8]. Four micro-actuators are at right angles to each other and the central platform and are placed in such a way that their movement follows the movement of hot and cold arms when an electric potential or heat is applied. This arrangement upon the application of electric potential and heat has an ability to deflect both inwards as well as outwards depending upon the voltage applied. The platform can be tilted diagonally or side wise by grounding the electrical potential to that particular micro-actuator. The materials used are: *Polysilicon:* Anchors, central platform, flexural spring *Aluminium:* Hot arms, Anchors, Flexure, Cold arms and Connectors.The parametric values and dimensions for microaligning arrangement are given in tables below.

Table 1: Properties of materials used

Table 2: Dimensions of the design.

Parameters	Aluminium	Polysilicon
Poisson ratio(ν)	0.33	0.22
Dielectric constant(ε)	1.8	4.5
Thermal conductivity(W/m/K)	237	34
Coefficient of thermal expansion	2.6e-6	2.6e-6
Heat capacity (J/kg/K)	898.7	678
Density (kg/m³)	2700	2320
Young's modulus (Y)	70e9	160e9
Electrical conductivity (S/m)	3.538e7	8e6

Components	(Width) X (Heig (Thickness)µm
Anchor [4]	400 x 410 x 10
Cold arms[4]	555 x 45 x 10
Hot arms[16]	640/705 x 10 x 5
Flexural Springs[4]	7 x 555 x 5
Platform radius	300
Connector	40 x 20 x 10

7 SIMULATION RESULTS AND DISCUSSIONS

The simulation results for the structure microaligning cum positioning arrangement were obtained by using COMSOL Multiphysics 4.3b. The results so obtained for various parameters viz. Total Displacement, Displacement along Z- Axis, Displacement along Y-Axis, Displacement along X-Axis, Output Temperature, Von-Mises Stress in the structure, Current Density are tabulated and plotted as below. Along with that the snapshots of the 3D results and shape of the structure under different conditions are also given.

Table 3: At Temperature To = 290K

Input Voltage [V]	Von-Mises Stress {GPa]	Total Displacement [µm]	Displacement Along X-axis [µm]	Displacement Along Y-axis [µm]	Displacement Along Z-axis [µm]	Output Temperature [K]	Current Density x 10^9 A/m^2
0	0.045	1.2	0.04	0.04	1.2	290	0
0.01	0.024	0.66	0.02	0.02	-0.66	297	35.5
0.02	0.23	6.22	0.22	0.22	-6.22	320	71.0
0.03	0.581	15.5	0.55	0.55	-15.5	357	107
0.04	1.07	28.5	1.02	1.02	-28.5	410	142
0.05	1.69	45.1	1.61	1.61	-45.1	477	178
0.06	2.46	65.5	2.34	2.34	-65.5	560	213
0.07	3.36	89.6	3.2	3.2	-89.6	657	249
0.08	4.41	117	4.19	4.19	-117	769	284
0.09	5.59	149	5.32	5.32	-149	897	320
0.10	6.91	184	6.58	6.58	-184	1039	355

Table 4: At Temperature To = 310K

Input Voltage [V]	Von-Mises Stress {GPa]	Total Displacement [µm]	Displacement Along X-axis [µm]	Displacement Along Y-axis [µm] +/-	Displacement Along Z-axis [µm]	Output Temperature [K]	Current Density x 10^9 A/m^2
0	0.24	6.4	0.23	0.23	-6.4	310	0
0.01	0.31	8.25	0.30	0.30	-8.25	317	35.5
0.02	0.52	13.8	0.5	0.5	-13.8	340	71.0
0.03	0.87	23.1	0.83	0.83	-23.1	377	107
0.04	1.36	36.1	1.29	1.29	-36.1	430	142
0.05	1.98	52.7	1.89	1.89	-52.7	497	178
0.06	2.75	73.1	2.61	2.61	-73.1	580	213
0.07	3.65	97.2	3.47	3.47	-97.2	677	249
0.08	4.7	125	4.47	4.47	-125	789	284
0.09	5.88	157	5.59	5.59	-157	917	320
0.10	7.2	192	6.85	6.85	-192	1059	355

Table 5: At Temperature To = 330K

Input Voltage [V]	Von-Mises Stress {GPa]	Total Displacement [µm]	Displacement Along X-axis [µm]	Displacement Along Y-axis [µm]	Displacement Along Z-axis [µm]	Output Temperature [K]	Current Density x10^9 A/m^2
0	0.53	14	0.51	0.51	-14	330	0
0.01	0.60	15.9	0.57	0.57	-15.9	337	35.5
0.02	0.81	21.4	0.77	0.77	-21.4	360	71.0
0.03	1.16	30.7	1.1	1.1	-30.7	397	107
0.04	1.65	43.6	1.56	1.56	-43.6	450	142
0.05	2.27	60.3	2.16	2.16	-60.3	517	178
0.06	3.04	80.7	2.89	2.89	-80.7	600	213
0.07	3.94	105	3.75	3.75	-105	697	249
0.08	4.99	133	4.74	4.74	-133	809	284
0.09	6.17	164	5.87	5.87	-164	937	320
0.10	7.49	199	7.12	7.12	-199	1079	355

7.1 Displacement

The tables 3-5, figure 3 and plot 1 show the various displacements results in micro-alignment system when an input voltage of magnitude varying from 0V-0.1 V in steps of 0.01V is applied at the electrical contacts. From the graphical results obtained we can see that maximum displacement is along z axis at all temperatures. The displacement along z-axis is along negative axis whereas total displacement is along positive z-axis. Displacement along x-axis and y-axis is symmetric and equal. Thus the structure obtained can move vertically as well as horizontally upon electrothermal excitation.

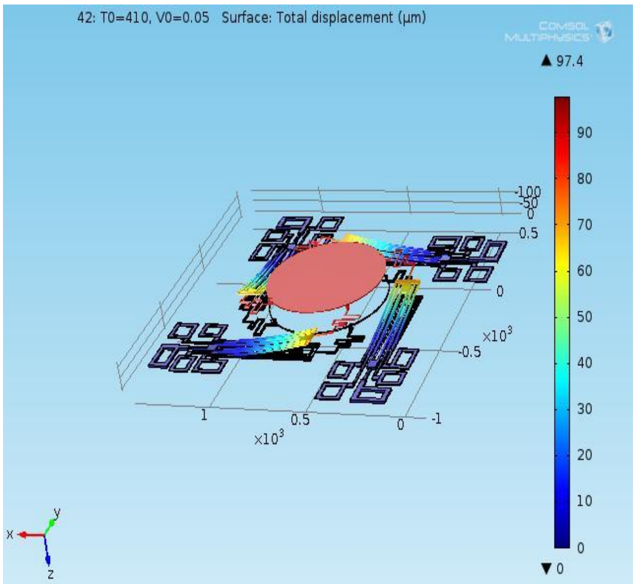
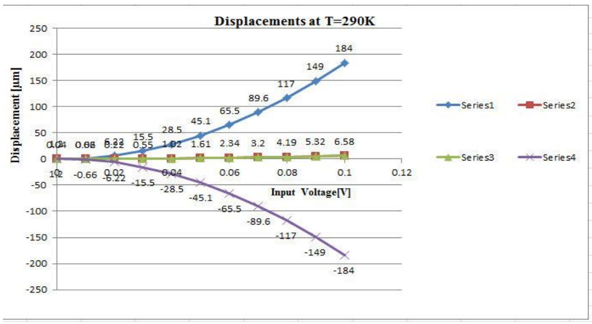


Fig - 3: Displacement Distribution.



Plot-1: Input Voltage Vs Disp. along x,y and z-axis

7.2 Von-Mises Stress

The figure 4, tables 3-5 and plot 2 show the various von-Mises ranges in micro-alignment system when an input voltage of magnitude varying from 0V to 0.1 V in steps of 0.01V is applied at the electrical contacts at constant temperature. From the graphical results obtained we can see that it ranges is from 0.43GPa to 7.49GPa, as we can see in most areas of the structure the blue color represents lowest von-Mises stress. This shows that structure is stable throughout the voltage and temperature ranges.

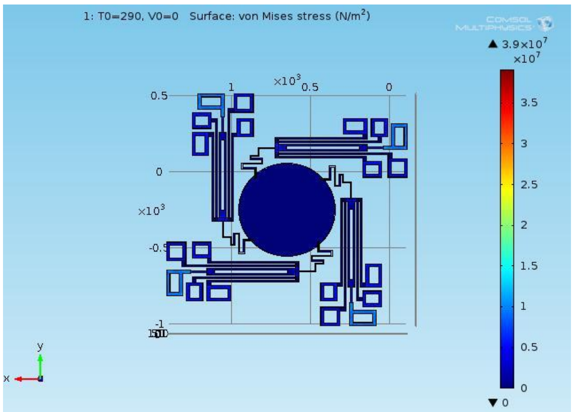
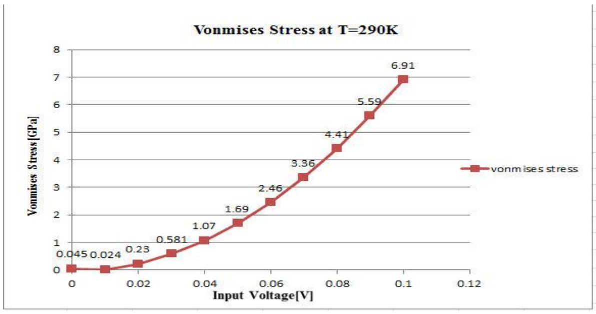


Fig – 4: Von-Mises Distribution.



Plot-2: Input Voltage Vs von-Mises stress

7.3 Temperature

The fig 5, tables 3-5 and plot 3 show the various temperature ranges in micro-alignment system when an input voltage of magnitude varying from 0V to 0.1 V in steps of 0.01V is applied at the electrical contacts at constant temperature. From the graphical results obtained we can see that maximum temperature range is between 450K to 460K or lower than that, while in few components it is near to maximum. The tilted position of the central platform is shown in the following fig -6. This is obtained when voltage applied is set to 0V for any three of the actuators supporting the platform. The maximum displacement obtained on the raised side is 135µm.

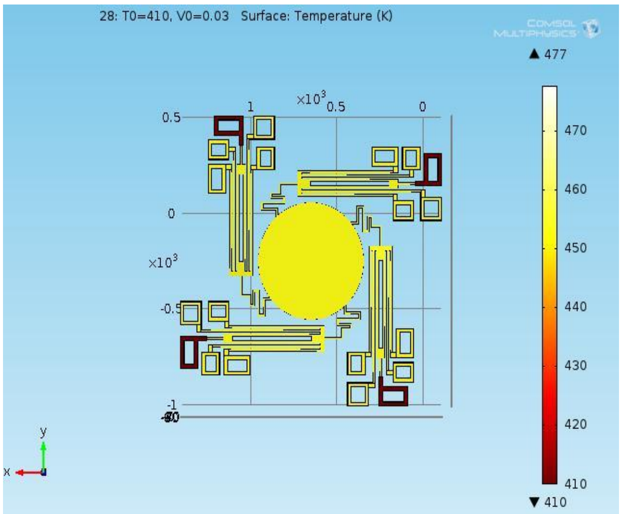
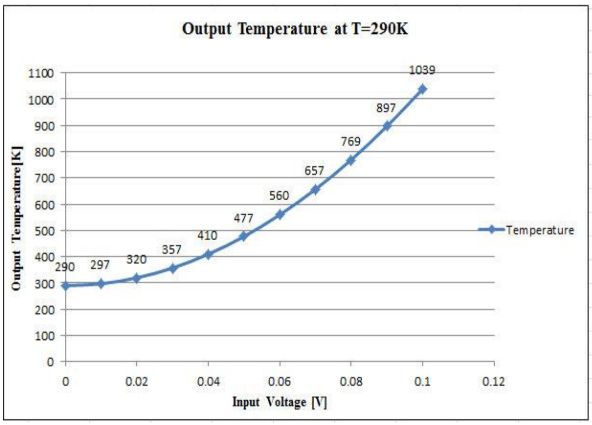


Fig – 5: Temperature Distribution



Plot -2: Input Voltage Vs Output Temperature

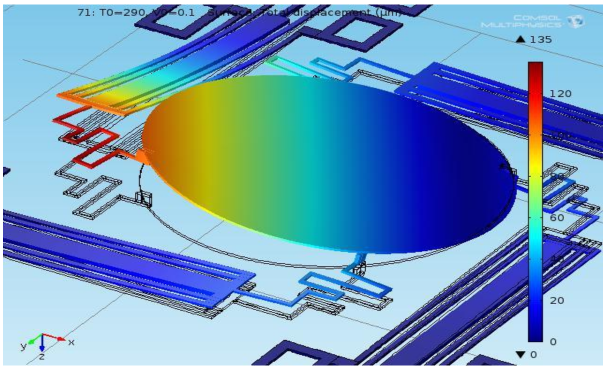


Fig- 6: Tilted Central Platform

8 CONCLUSION

A 3-D electrothermal "Microaligning Cum Positioning Arrangement- An Application of Microactuators" has been designed using COMSOL 4.3b. The results conclude that the electrothermal aligning system is highly sensitive to geometrical and material variations. It has been realized that longer hot arms produce more deflections but a tradeoff lies in the sense that, on increasing the length of the hot arm, resistance also increases, so there is a chance of failure due to stiction to the substrate. In it the modified W-beam micro-actuator alpha and beta help keep the required input voltage and structure bulkiness lower. On decreasing the gap between the beams of the actuators, tip displacement increases, which directly control the movement of the central stage. Thus it is desired to use longer hot arms. A proper ratio has to be maintained between the gaps and between the lengths of the arms. In this work, the effect of dimensional change of the hot arm, cold arms gap between the arms, applied voltage, different materials, and various combinations of materials is realized. Thus, these designs are easy to fabricate and provides large displacements even at smaller applied voltages.

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