Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

# Design and Simulation of MEMS Based Electrothermal Micromirror for 3D Spatial Movement

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**Abstract:** In this paper, we have addressed the design and simulation results of an electrothermally driven micromirror that is capable of producing in-plane as well as out-of-plane displacements. The coupled multiphysics simulation and study of the electrical, thermal and - most importantly - the mechanical behavior of the mirror system is done using COMSOL Multiphysics. The device has an in-plane displacement range of 3.56 µm (1.78 µm in either direction). An out-of-plane displacement of approximately 22µm is achieved for an input voltage of only 2V. The ability of precise control of movement of the micromirror in space is likely to lead to potential applications in diverse fields.

**Keywords:** Electrothermal actuators, MEMS, Micromirror

## 1. Introduction

Micromirror is a versatile MEMS device, which finds use in many application areas. While research in this particular field has been carried out for more than 30 years, the actual push came in the 90's for the development of optical switching systems. Specifically, significant efforts have been made for the development of scanning micromirrors for optical switching and display applications. They are also used in biomedical fields for non-invasive optical imaging techniques such as optical coherence tomography and nonlinear optical microscopy for cancer detection [1]. While out-of-plane rotation of the mirror plate is more relevant for switching applications, in order to increase the versatility, in-plane motion is also necessary. In this paper, we have designed a thermally actuated micromirror capable of moving both in vertical and horizontal directions.

We have chosen thermal actuating mechanism as MEMS based electrothermal 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 low speed. Since the deflection depends on the heat transfer rates, the heating, and more importantly, the cooling rate limits their speed of operation to up to kHz order [2]. Thus thermally actuated micromirrors are suitable for high deflection, low frequency operations.

The principle of operation of electrothermal actuation is non-uniform Joule heating leading to differential thermal expansion, resulting in the deformation of the structure. An often used electrothermal actuator is U-beam type [3], as demonstrated by Guckel in 1992. Conventional U-beam electrothermal actuators [Figure 1] have the limitations of producing deflections along a single direction. In order to produce complete in-plane movement, we have investigated a bidirectional (i.e., along positive and negative X- or Y- axis) electrothermal actuator design. Such an actuator has been demonstrated by Venditti et al [4].

A simple way to generate an out-of-plane bending is to use a thermal bimorph, composed of two material layers with different coefficient of thermal expansions (CTE). Typically, the layers consist of one material with a high CTE, such as a metal like Al, and another material with a low CTE, such as a dielectric like $SiO_2$. When a voltage is applied, the bimorph temperature will change; so the high CTE material will expand much more than the low-CTE material, yielding a bending of the bimorph. This bending results in a complex displacement composed of both an angular rotation as well as a vertical displacement, which can be used for the tip tilt motion of the micromirror.

In this paper, we utilize both this in-plane and out-of-plane actuation concept to design a micromirror that is capable of producing three dimensional movements. The design concept and principle of operation of different modes of the mirror are described first. Finite element simulations of the device using COMSOL

Multiphysics are then discussed. Also, an analytical model for dynamic cooling response of the in-plane actuator has been investigated.

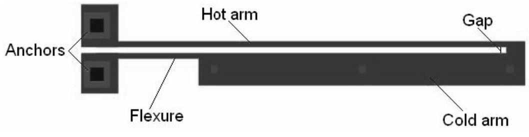


**Figure 1.** Schematic diagram of a conventional U-beam electrothermal actuator. Applied voltage produces a high temperature in the thin (hot) arm compared to the wide (cold) arm due to Joule heating, which causes its length to increase. Differential length change bends the structure downward (unidirectional).

## 2. Design concept

Two types of thermal actuation mechanism are used in the designed device. For in-plane movement poly-silicon made bidirectional actuator is used [Figure 2]. This 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. Bidirectional motion of the designed actuator is depicted in Figure 3. The advantage in using these W-shaped actuators for the micromirror is that by selectively applying voltages among the four actuators, the mirror can be displaced laterally more compared the conventional U-beam actuators, using a push-pull method.

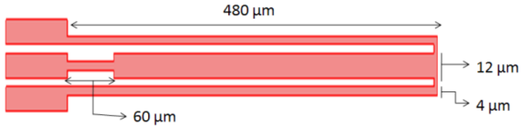


**Figure 2.** Schematic of the bidirectional actuator. When voltage is applied between bottom thin arm and the common wide arm, the device moves upwards. Downward motion results when voltage is applied to the upper thin arm. Dimensions are labeled.

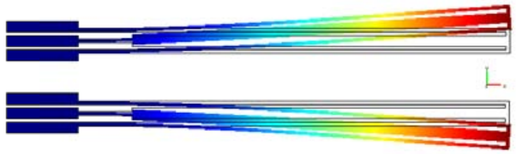
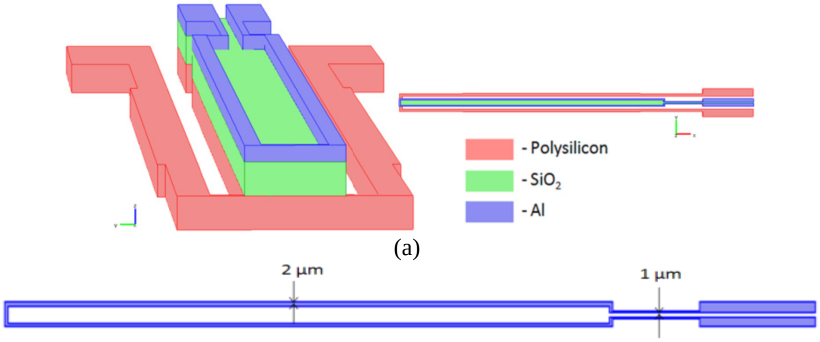


**Figure 3.** Bidirectional in-plane motion of the actuator.

For out-of-plane movement, bimorph actuator composed of Al and silicon dioxide layers deposited above the polysilicon in-plane actuator layer [Figure 4]. First, $SiO_2$ is deposited above the entire wide arm of the in-plane bidirectional actuator. Then patterned Al layer is deposited above the insulating $SiO_2$. When current is passed through the Al layer, it bends more due to its high CTE, than $SiO_2$ or polysilicon layers. Thus, the actuator moves vertically as shown in Figure 5. One advantage of this particular configuration is that as the metal is deposited above the wide arm of the in plane actuator, so when voltage is applied only to the in-plane actuator, the wide arm remains relatively cold and thus does not warm the Al layer. So reduces the chances of offset vertical displacements.



(a)

(b)

**Figure 4.** (a) Schematic diagram of the bimorph and (b) the patterned Al layer. Dimensions are labeled.

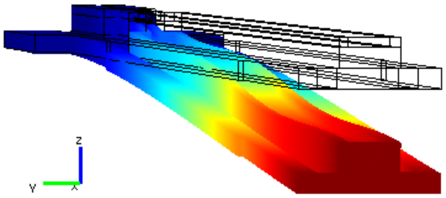


**Figure 5.** Vertically displaced bimorph actuator.

In the complete mirror structure, we have attempted to incorporate the features for both in-plane and out of plane motion. Consequently, four actuators are attached to the mirror plate 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. As shown in Figure 6, the electrothermally actuated micromirror is symmetrically designed. The mirror is 100 µm square and made of polysilicon. The thickness of the polysilicon, $SiO_2$ and Al layers are 4, 4 and 2 µms respectively. The micromirror design is consistent with the design rules of the "Polysilicon Multi-user MEMS Process" (PolyMUMPs) process.

## 3. FEM analysis using COMSOL Multiphysics

In order to analyze the static behavior of the micromirror, COMSOL Multiphysics FEM software is used. The coupled multiphysics simulation and study of the electrical, thermal and most importantly, the mechanical behavior of the mirror is done using thermal-electric-structural interaction mode of COMSOL MULTIPHYSICS MEMS module. For simulations of the micromirror as shown in Figure 6, the ends of the actuators are mechanically fixed. All other boundaries are kept free to move.

For in-plane movement of the mirror, DC voltages have been applied selectively to the ends of the arms of the four polysilicon actuators. For out-of-plane movement, voltages have been applied across the metal layer. When voltage is applied, the structure warms up non-uniformly due to resistive Joule heating. Resistivity is a temperature dependent parameter. It varies with temperature according to the following equation.

$$\rho = \rho_0[1 + \alpha_R(T - T_0)] \qquad (1)$$

Where, $\rho_0$ is the resistivity at a reference temperature $\alpha_R$ is the temperature co-efficient of resistivity (TCR), and $T_0$ is the reference temperature. The values of TCR of polysilicon and Al are given in the Table-1 (Appendix).

The fundamental equation that describes the heat transfer problem [6] is the so called heat diffusion equation:

$$\nabla^2 T + \frac{q}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (2)$$

Where α $(= \frac{k}{\rho c})$ is thermal diffusivity, T is the temperature distribution, k is the thermal conductivity of the material, ρ represents the density, c is the specific heat capacity, and q accounts for the volumetric heat loss. In the steady state, right hand side of the equation (2) is equal to zero. Temperature distribution of the device is obtained solving equation (2) numerically.

In the thermal boundary conditions, the faces which are at contact with the substrate are set at a constant temperature (300K), modeling an infinite heat sink. This is quite obvious as all other boundaries interact thermally with the surroundings by conduction through thin layers of air so some part has to act 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

$$q(T) = h(T - T_0) \qquad (3)$$

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 equation (3) is not exact but a good approximation.

In case of in-plane motion, application of voltage causes the thin arm of the actuators to expand significantly more than the wide arm. Therefore the expansion of the wide arm can be neglected compared to the expansion of the thin arm. Thus the new length of the thin arm due to thermal expansion can be approximated as:

$$L_{new} = \int_0^{L_t} [1 + \alpha(T(x) - T_0)]dx \qquad (4)$$

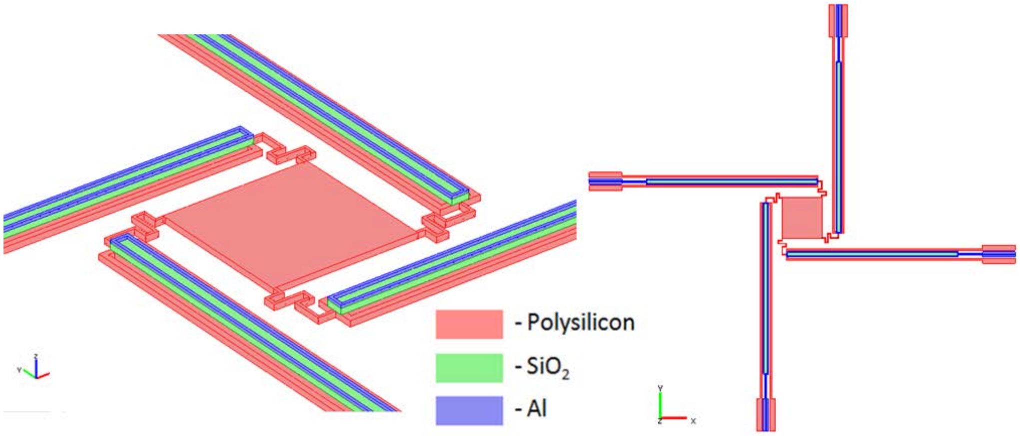
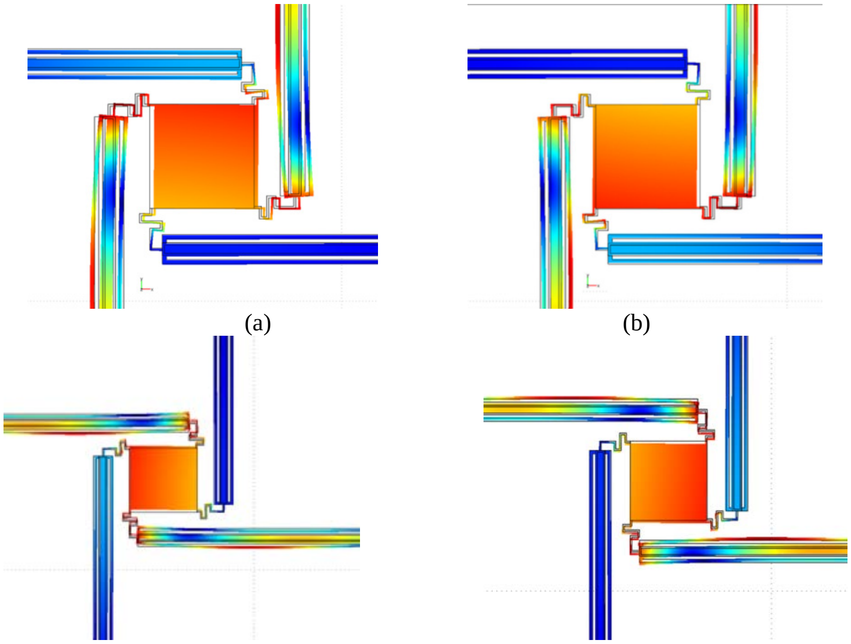


**Figure 6.** Designed micromirror structure with four in-plane actuators and four out-of-plane actuators.



(a) (b)

(c) (d)

**Figure 7.** (a) & (b) shows the displacement of the mirror along positive and negative direction of the x-axis. (c) & (d) shows the same along positive and negative directions of the y-axis.

Here, T(x) is the temperature distribution along the hot arm, $L_t$ is the length of the thin arm, $\alpha$ is the thermal coefficient of expansion of the material (polysilicon in this case).

Figure 7 shows the simulation results of the laterally displaced mirror. As shown in Figure 7(a) & (b), to move the mirror along the x-axis, voltage has been applied to the left and right actuators. Similarly for y-movement, top and bottom actuators are actuated [Figure 7(c) & (d)]. Furthermore, voltage can be applied to all the four actuators to move the mirror plate diagonally as shown in Figure 8. The variation of the in-plane displacement with voltage is plotted on the Figure 9. As shown, displacement increases non-linearly with voltage. The maximum displacement achieved is 1.78 µm with 10V applied voltage. Thus as the mirror shows bidirectional motion, so it can cover up to

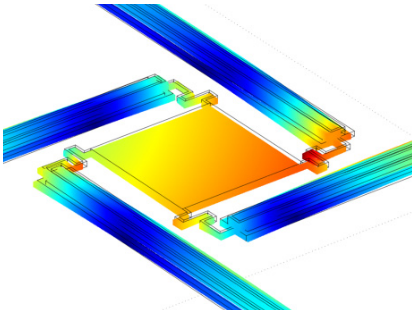


**Figure 8.** Diagonal (both x and y) movement of the mirror in its own plane

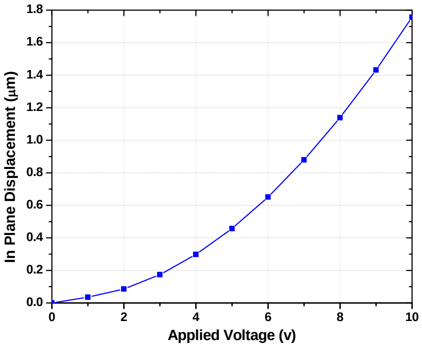


**Figure 9.** In-plane displacement as a function of input voltage

a total distance of 3.56 µm along x- or y-directions.

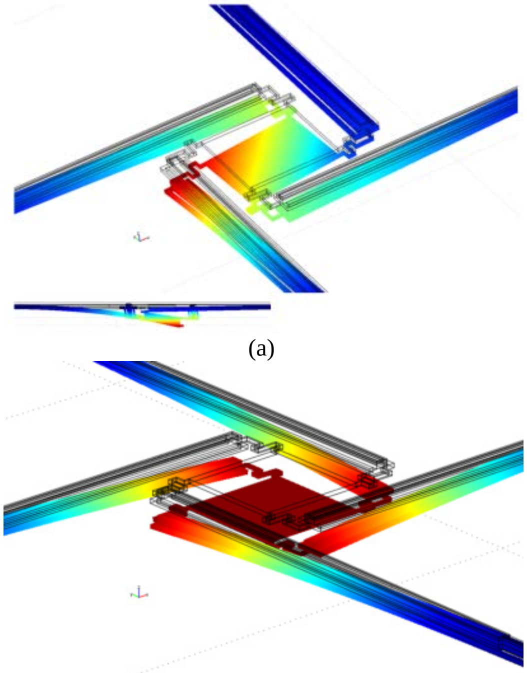
In case of out-of-plane bending, the bimorph beam theory, as reported by W.H. Chu et al (1993) [5], can be applied without major changes. Then the curvature due to thermal expansion mismatch obtained from bimorph beam theory is:

$$k = \frac{6w_1w_2E_1E_2t_1t_2(t_1+t_2)(\alpha_1+\alpha_2)\Delta T}{(b_1E_1t_1)^2+(b_2E_2t_2)^2+2b_1b_2E_1E_2t_1t_2(2{t_1}^2+3t_1t_2+2{t_2}^2)} \quad (5)$$

Where E is the Young’s modulus, α is CTE, w is the width, t is the thickness of the layers and ΔT is the change in temperature between the ambient and the stacked layers. Now if L be the length of the bimorph beam, then vertical deflection at the tip of the bimorph is given by:

$$d_{vertical} = \frac{kL^2}{2} \quad (6)$$

Figure 10 shows the simulation results of the vertically deflected mirror. As shown in Figure 10(a), a single bimorph layer is actuated to tilt the mirror plate. All the four bimorphs can be simultaneously actuated to move the entire mirror plate downward. Such simulation is shown on the Figure 10(b). If the mirror can move vertically, then it could improve the focusing in microscopy. The variation of the out-of-plane displacement with voltage is plotted on the Figure 11. Deflection increases almost linearly with voltage. The simulated structure is capable of producing large out-of-plane deflection (~22 µm) of the mirror for small applied voltage (2V).



(a)

(b)

**Figure 10.** (a) Shows the tilting of the mirror plate. Vertically downward motion of the mirror is depicted on (b).

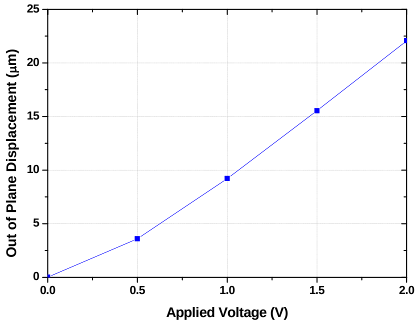
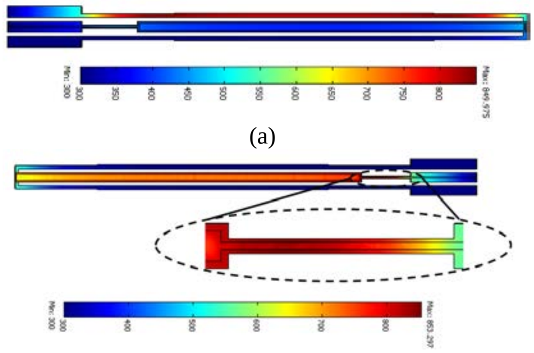


**Figure 11.** Out-of-plane displacement as a function of input voltage

The key factor that limits the performance of an electrothermal device is temperature. As reported in [4], that the temperature of a polysilicon device should be kept under 1200K to avoid thermal failure, so analysis is done for in-plane actuation keeping the maximum temperature below 1000K. During bimorph actuation, the maximum temperature is kept below 900K (Maximum allowable temperature) for the same reason. As shown on Figure 12(a), in case of in-plane actuation, maximum temperature is generated in the thin polysilicon arm. Whereas, for vertical deflection, maximum temperature is generated at the neck of the Al layer [Figure 12(b)]. The corresponding variations of temperature with voltage are shown in plots of Figure 13(a) and (b). Limit of maximum temperatures, as mentioned in the above discussions, have been maintained in both the cases.



(a)

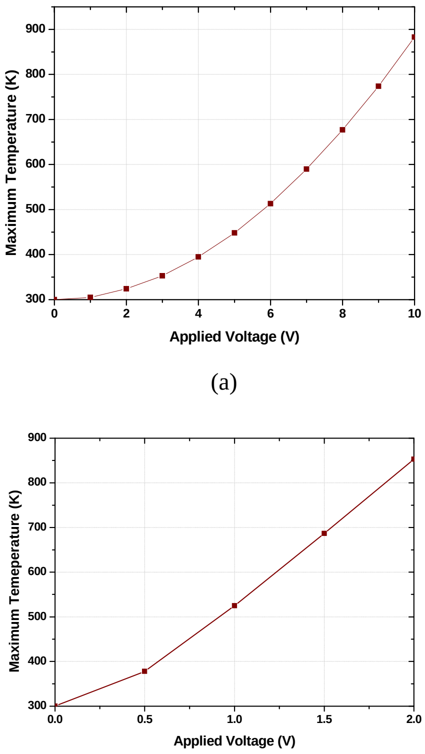
(b)

**Figure 12.** (a) Temperature profile of the actuator in case of in-plane movement. Figure (b) shows the temperature profile in case of out-of-plane bending.

## 4. Transient analysis of cooling

The 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 [6].

Though we can estimate the transient performance of the device based on the principles of heat transfer. As reported by Varona et al [6], the cooling transient of the structure, assuming that it is getting convectively cooled, is given by:



(a)

(b)

**Figure 13.** Maximum temperature as a function of input voltage. (a) in-plane actuation. (b) out-of-plane actuation.

$$T(t) = T_a + (T_i - T_a)e^{-t/\tau} \qquad (7)$$

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 result corresponding to the cooling transient under convective process for the in-plane actuation case is plotted in Figure 14. The cooling response time is of the order of milliseconds. So we can approximately say that the micromirror can be driven at frequencies of the order of kHz, which is in agreement with literature [2], as we mentioned before.

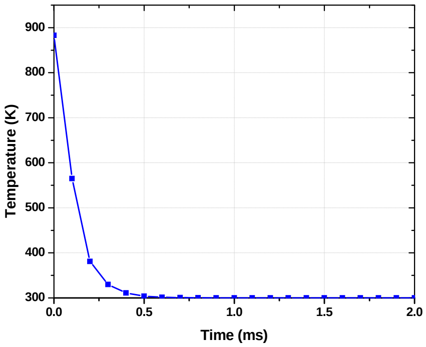


**Figure 14.** Estimated transient cooling response of the in-plane actuator.

## 5. Conclusions

In this paper, we have investigated a MEMS based micromirror that is capable of producing 3D spatial movement. Electrothermal actuation is used to achieve in-plane as well as out-of-plane movements in a single integrated device. Finite element based simulations are done using COMSOL Multiphysics software to model the performance of the micromirror. It is seen that the mirror can move up to 3.56 µm (1.78 µm in either direction) along x- or y- directions. During out-of-plane operation, approximately 22µm displacement is achieved for an input voltage of only 2V. In-plane displacements obtained are smaller, but the ability of precise control of movement of the micromirror in space is likely to lead to potential applications in diverse fields. The transient cooling response of the in-plane actuator is also discussed and response time is found to be satisfactory. The temperature generated due to Joule heating is however quite high, which is a typical drawback of the thermal actuation process. This is however offset by the simpler fabrication processes required for these devices.

## 6. Acknowledgements

COMSOL MULTIPHYSICS software was provided to the MEMS Design Center at the Institute of Radio Physics and Electronics, through the National Program on Micro and Smart Systems (NPMASS), Govt. of India. This work is part of the M. Tech thesis of D. Mallick who is a recipient of the GATE fellowship, awarded by Ministry of Human Resource Development (MHRD), Govt. of India.

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## 8. 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 |
| Temperature coefficient of resistivity of Al | 0.0039 | 1/K |
| Thermal conductivity of air | 0.04 | W/m.K |