Design and Simulation of MEMS Based Thermally Actuated Positioning System

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Introduction: An important application of MEMS technology is in the field of micro or nano-scale positioning and manipulation systems. The need of high precision positioning systems has increased drastically due to their crucial role in the fabrication of micro and nano-sized objects and assemblies.

Design Concept: Both in-plane and out-of-plane displacement capabilities have been incorporated on the same actuator structure using two layers (Poly1, Poly2) of PolyMUMPs process, as shown in the Figure 1.

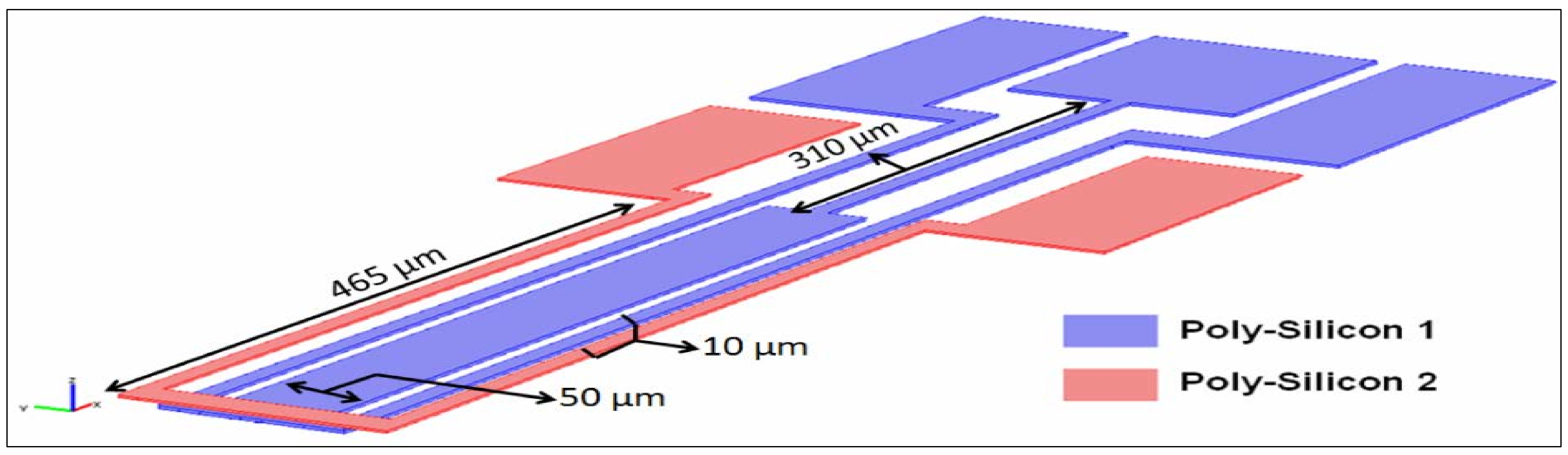


Figure 1: *Designed actuator arm composed of double layer of poly-silicon, used to produce in-plane as well as out-of-plane displacement*

- For in-plane movement, bidirectional actuator made of single layer of poly-silicon (Poly1) is used [Figure 2].
- 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 [Figure 3].

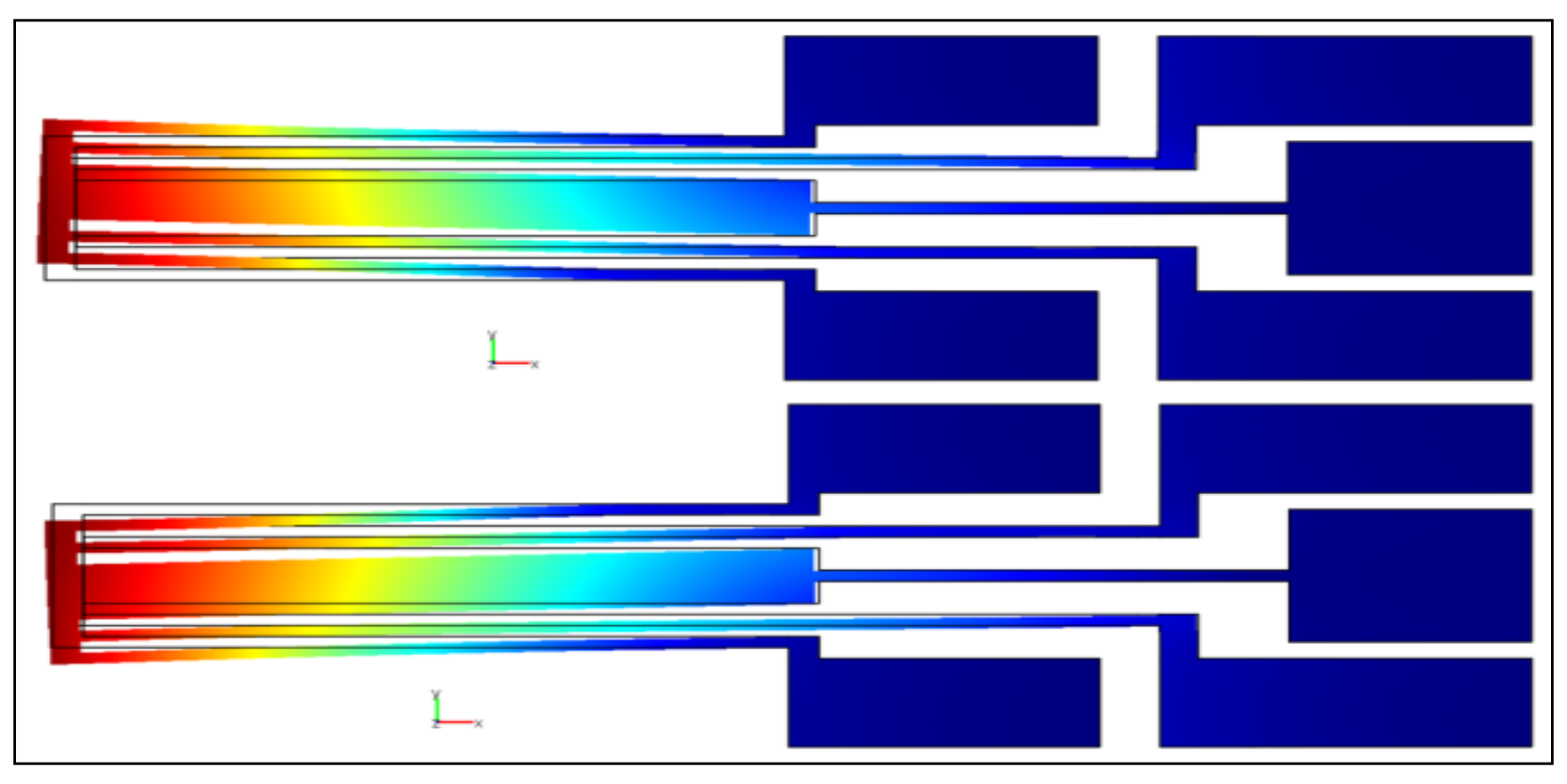


Figure 2: *Bidirectional in-plane motion of the actuator.*

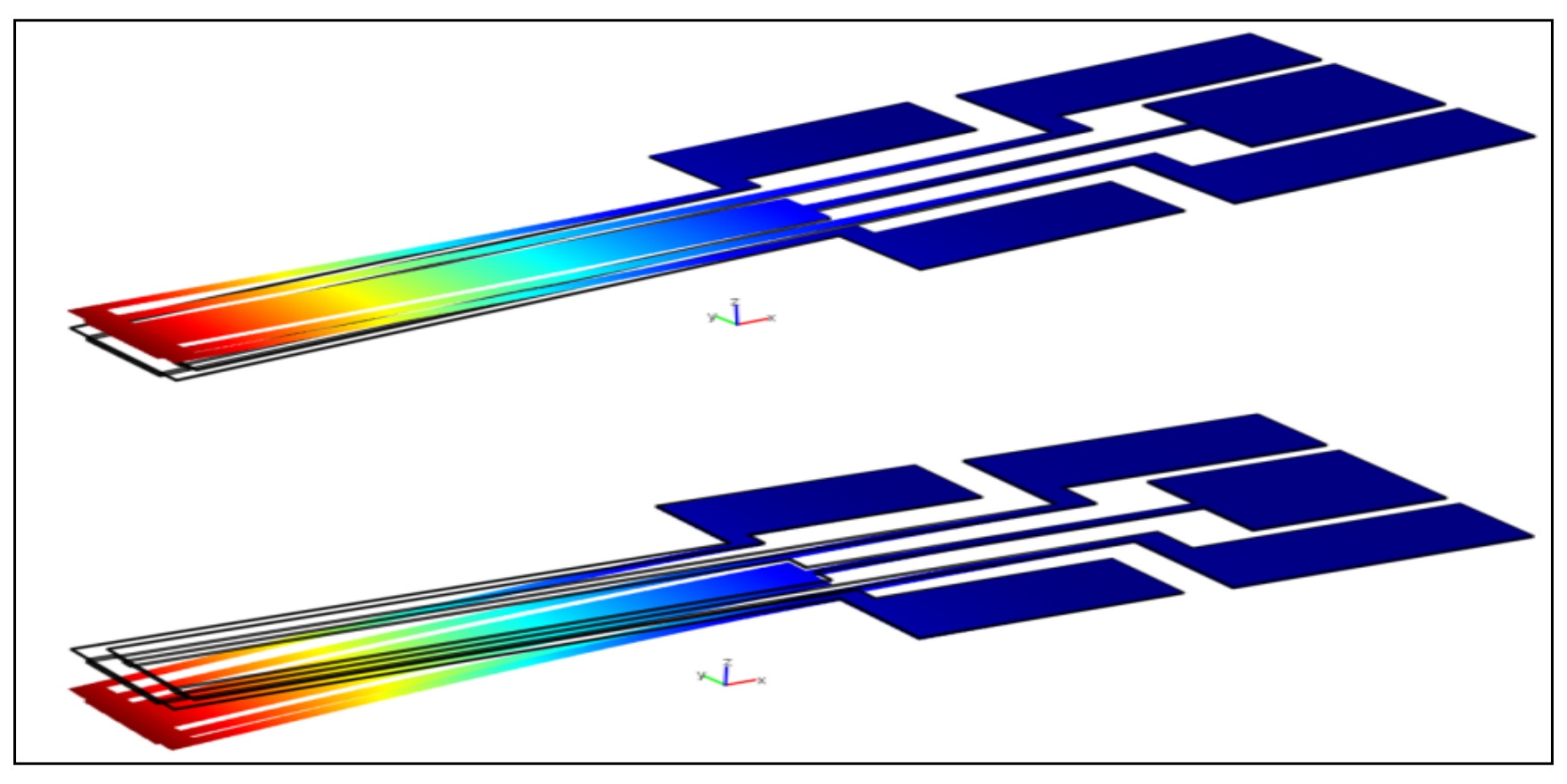


Figure 3: *Upward and downward motion of the actuator arm*

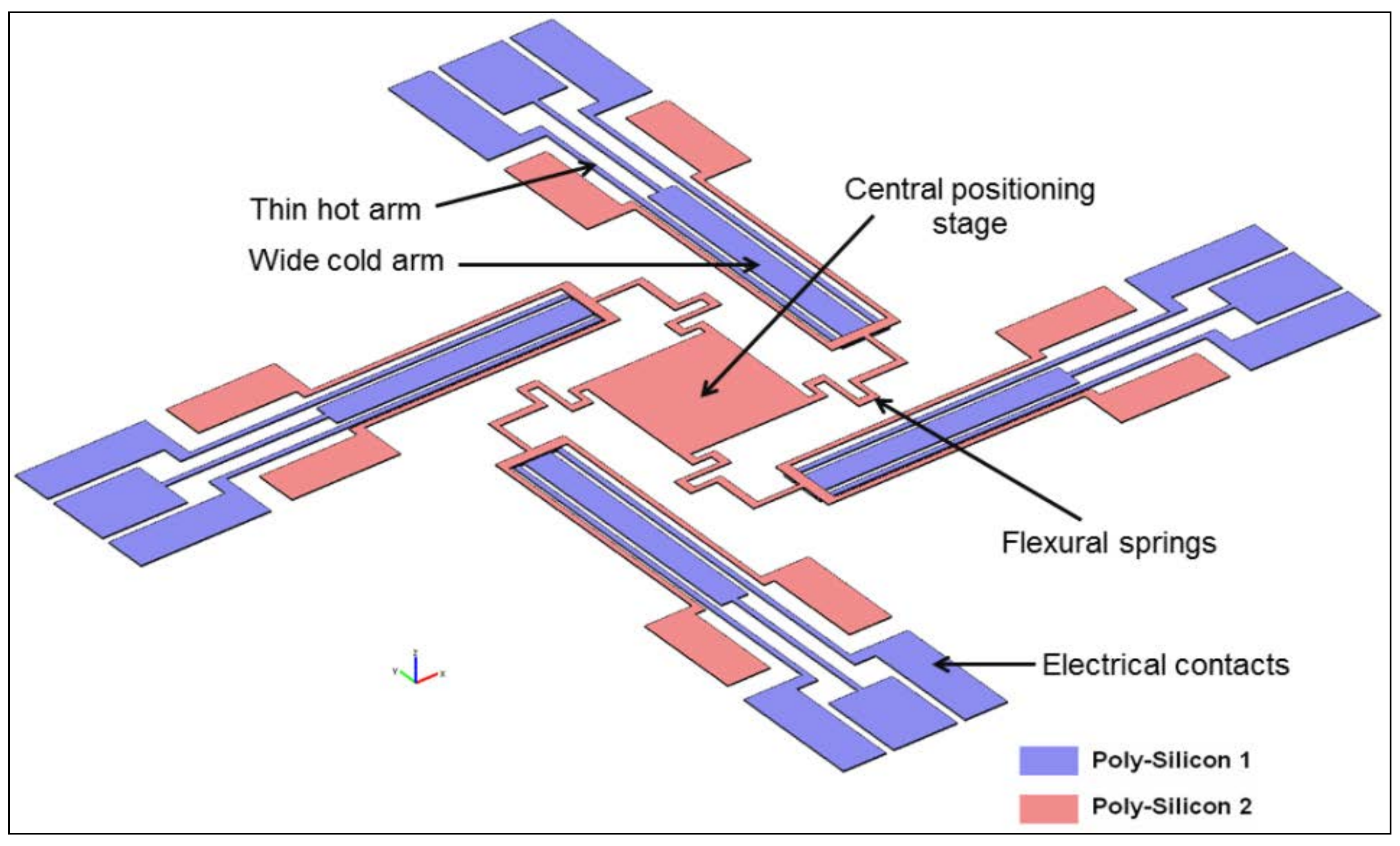


Figure 4: *Designed positioning system with four actuator arms attached to the central platform [250 µm square] via flexural springs.*

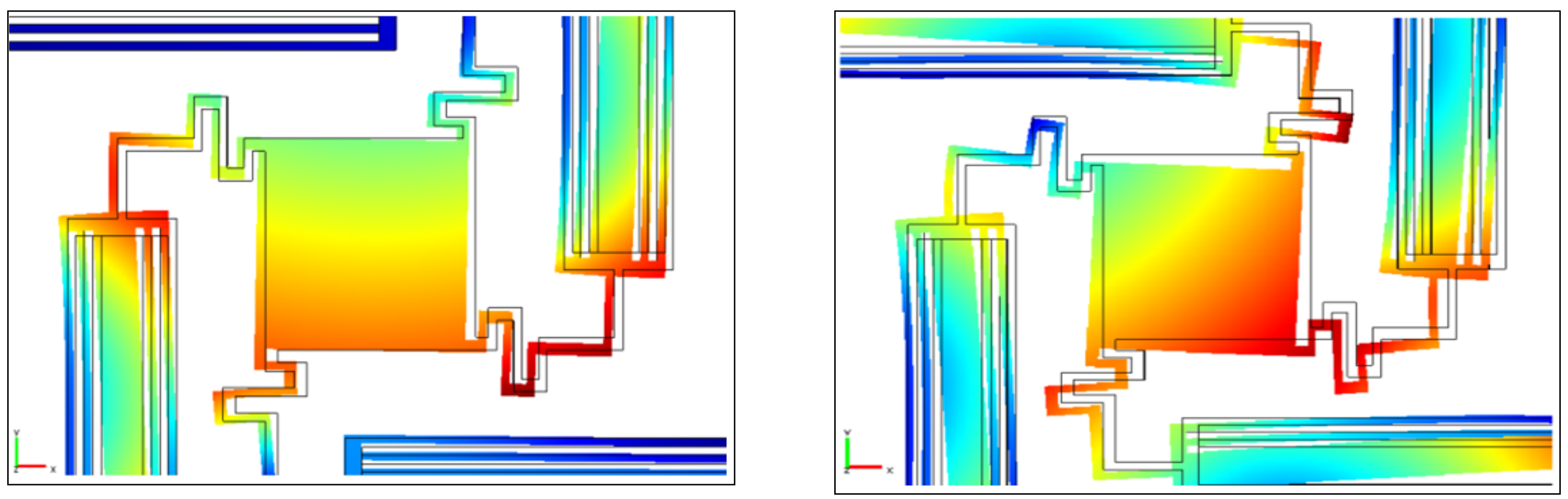
FEM Analysis: The coupled multiphysics simulation of the designed structure is done using thermal-electric-structural interaction mode of COMSOL MULTIPHYSICS MEMS module.

- In structural boundary conditions, the ends of the actuators are mechanically fixed. All other boundaries are kept free to move.
- 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.
- Heat release from the surfaces (due to convection and/or conduction) 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:

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

h= heat transfer co-efficient, T_o= temperature of the surrounding fluid

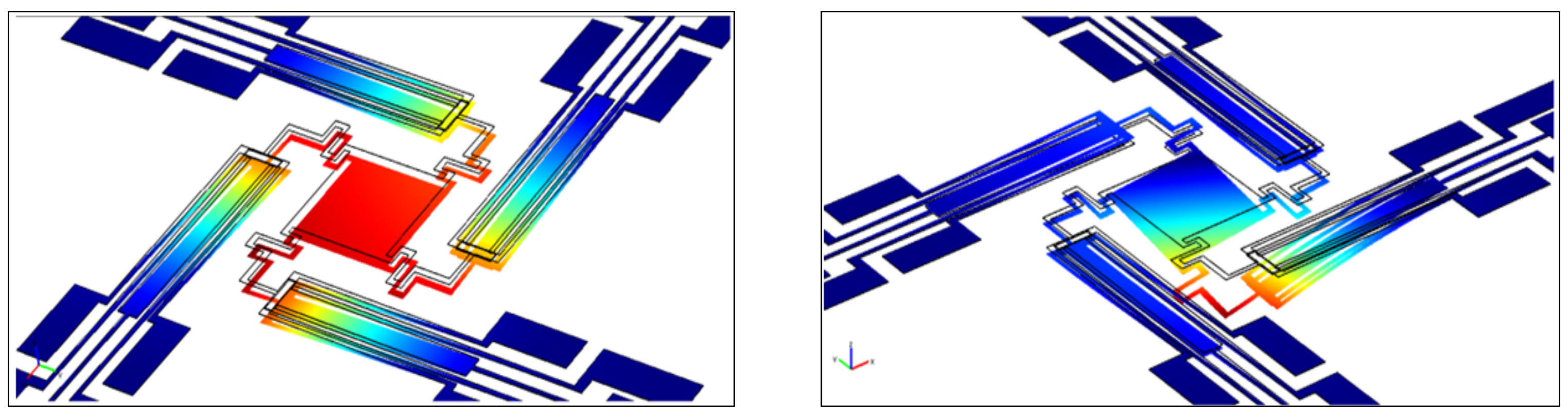
- For in-plane displacement of the positioning system, DC voltages have been applied selectively to the end of the arms (contact pads) of the four bottom poly-silicon (Poly1) actuators.



(a) (b)

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

- 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).



(a) (b)

Figure 6: *Out-of-plane displacement of the central stage. (a) along downward direction and (b) tilting motion*

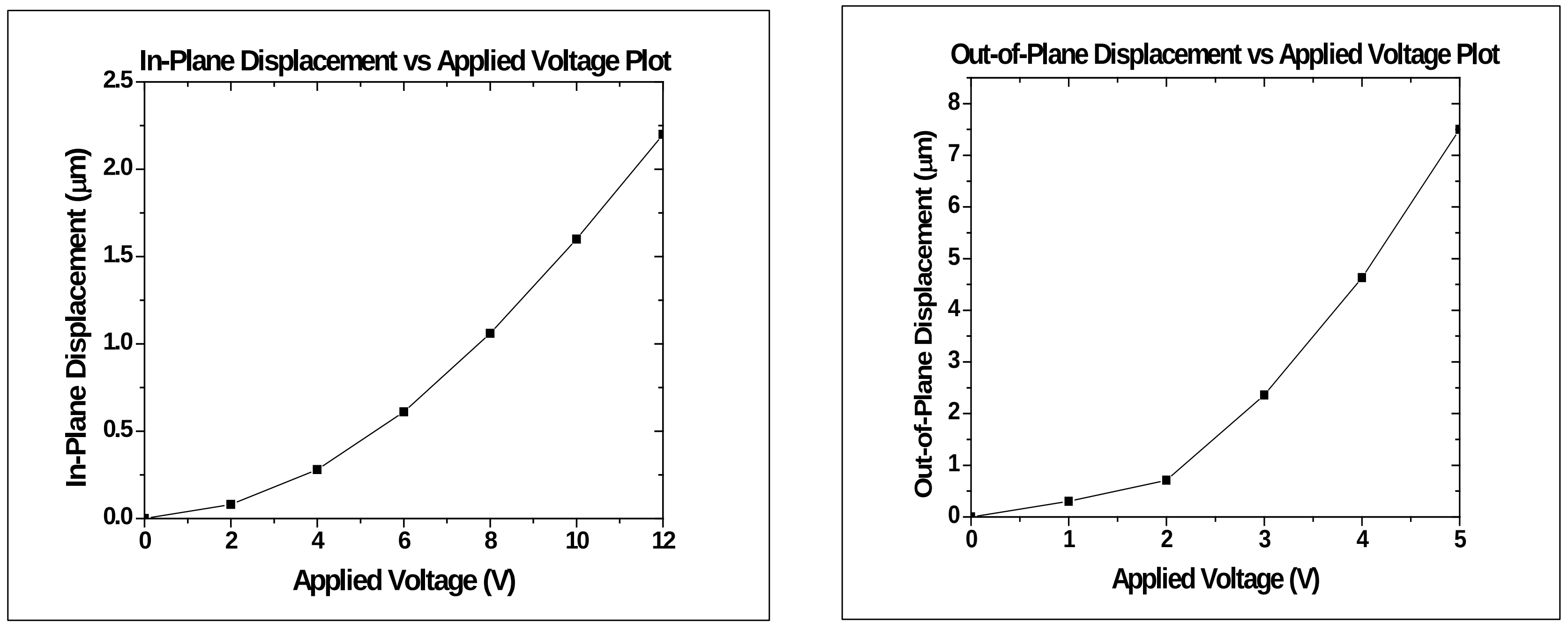


Figure 7: *In-plane and Out-of-plane displacements as a function of input voltage*

- The key factor that limits the performance of an thermally actuated device is temperature.
- The temperature of a poly-silicon device should be kept under 1200K to avoid thermal failure [1]. so analysis is done by keeping the maximum temperature well below that value.

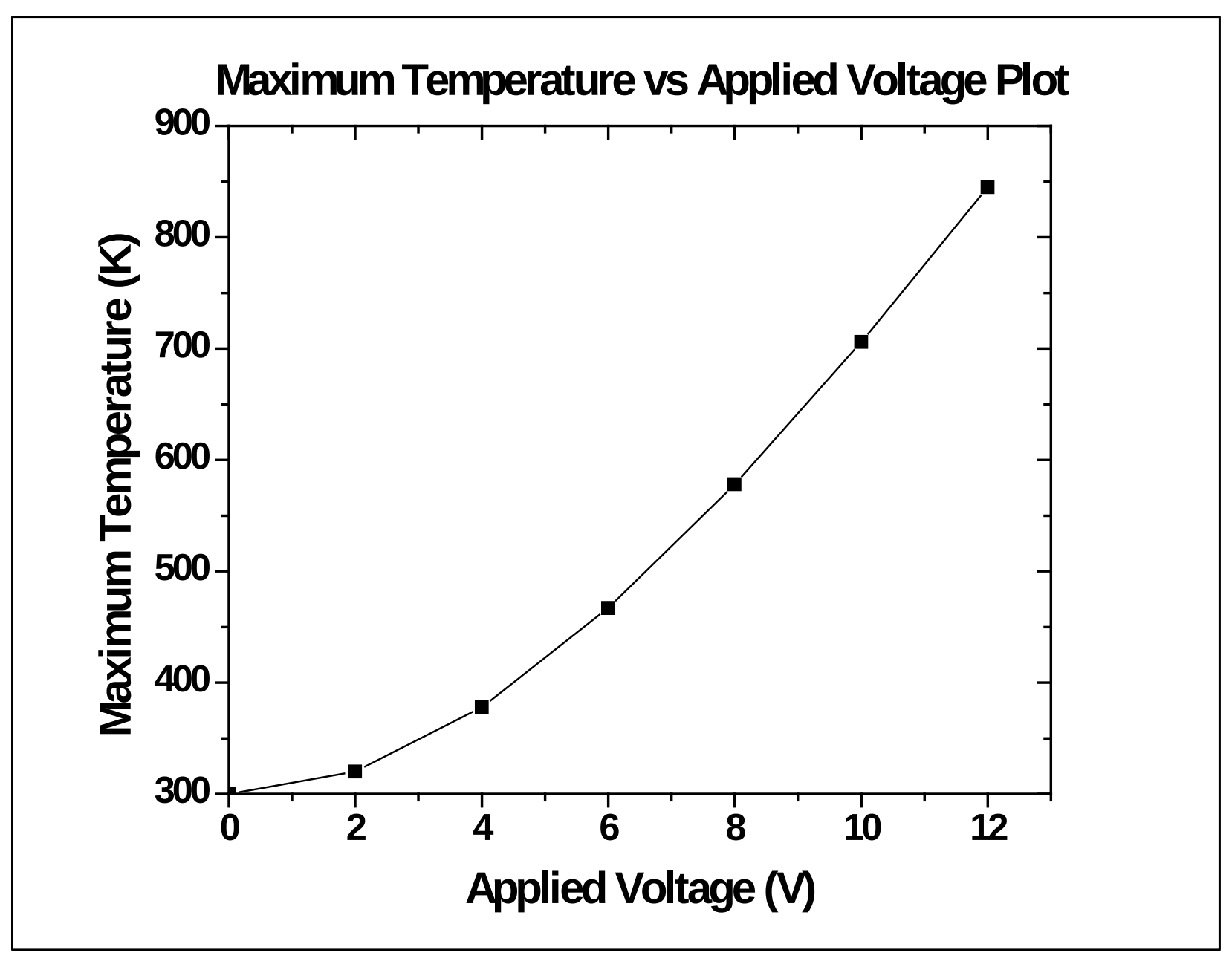


Figure 8: Maximum temperature as a function of input voltage

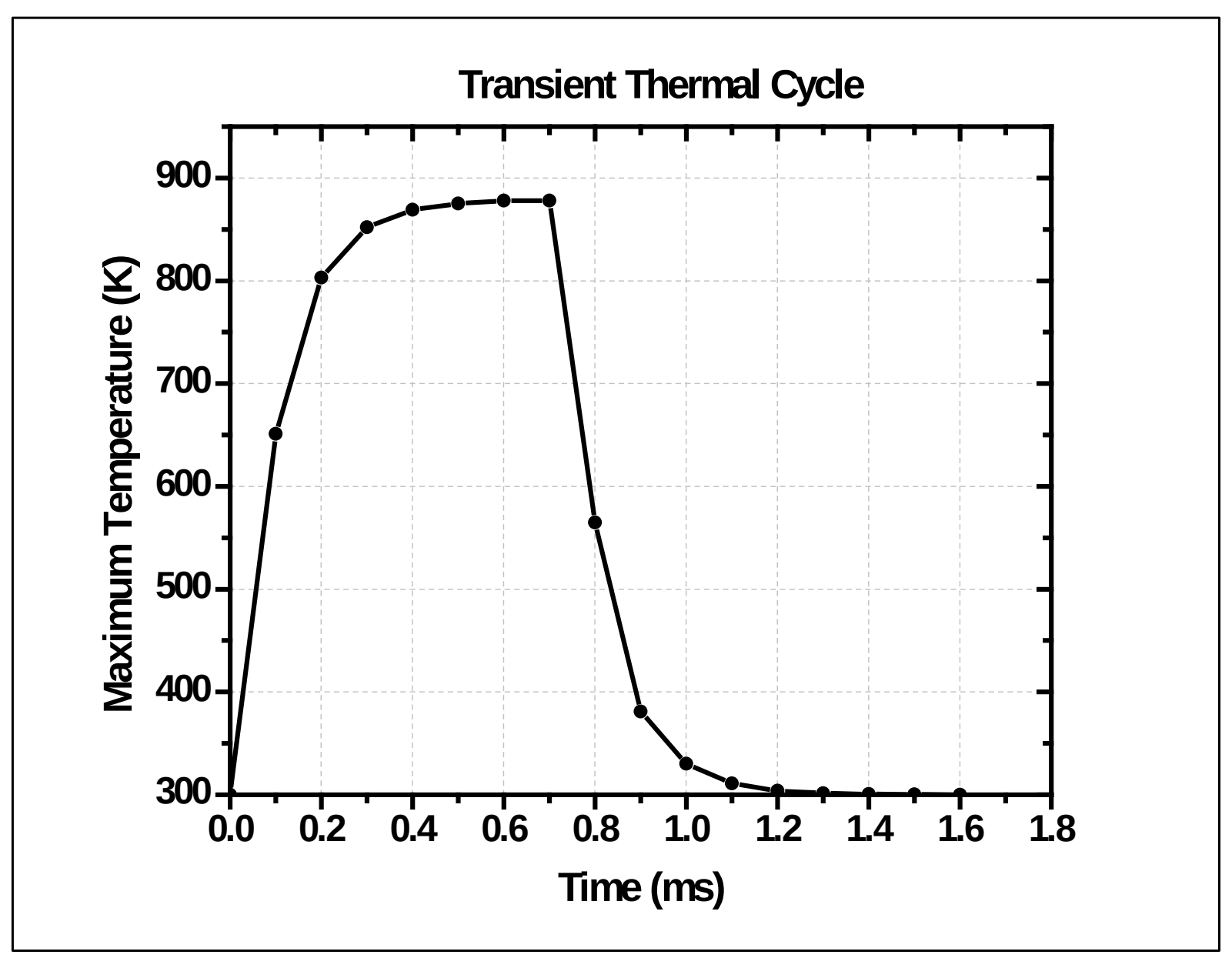


Figure 9: Estimated transient response of the poly-silicon actuator

Transient analysis of cooling: As reported by Varona et al [2], 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, τ =(ρcV/hA) 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).

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:

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

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

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

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.

Conclusion: The positioning system can move up to 4.4 µm (2.2 µm in either direction) along x- or y- directions. Approximately 15 µm of total out-of-plane displacement is achieved for an input voltage of only 2V. The micromirror can be driven at frequencies of the order of kHz.

References:

1. Venditti, Lee et al, An in-plane, bi-directional electrothermal MEMS actuator, Journ. of Micromech. and Microeng., 16, 2067-2070 (2006)
2. Varona, Hamoui et al, Modeling of MEMS Thermal Actuation with External Heat Source, Fourth CERAM, 591-596(2007)

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