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COMPUTATIONAL ANALYSIS OF RESPONSES OF MICRO ELECTRO-THERMAL ACTUATORS

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ABSTRACT

The electrical, thermal, and mechanical responses of surface micromachined (SMM) 2-beam actuators have been simulated using the Calagio code, a coupled physics analysis tool. The present analysis, unlike previous analyses, includes the surrounding air in the computational domain so that heat losses from the beams onto the silicon substrate will be accurately modeled. This setup is essential because the existing 'shape factor' correlations have difficulty to capture the three-dimensional geometric effect of the heat loss in the shuttle at the center that connects the bent beams. In addition, results from present analysis reveal that because the local heat flux can be extremely high, a significant temperature jump can occur across the air-structure interfaces.

NOMENCLATURE

q_n''	Heat flux normal to the wall (W/m^{-2});
R	Gas constant (J/Kg K);
T_w	Wall temperature (K);
T_s	Slip temperature (K);
γ	Specific heat ratio;
μ	Viscosity (N s/m^2);
σ_T	Thermal accommodation coefficient;
λ	Mean free path of gases (m).

INTRODUCTION

Previous analysis of the electrical, thermal, and mechanical responses of surface micromachined (SMM) actuators revealed that the existing computational models predicted the displacement generated by these actuators reasonably well [1, 2, 3]. However, there is not a comparison of temperature profiles between prediction and observation shown because very limited temperature measurement data exists. Recently, a set of 'high quality' experiments has been conducted to investigate the electro-thermal heating of these micro actuators [4]. In this data set, there is detailed measurement of the temperature profile along the I-shaped beams for an applied current. In addition, the resultant displacement is also obtained. Hence individual physical (electrical, thermal and mechanical) effect can be assessed in detail. Thermal model assessment using this set of data shows that discrepancy exists in the calculated and measured temperature profile along the beam [4]. The applied voltage in the model has to be modified in order to show reasonable agreement between predictions and measurement.

In those analyses [4], a 'shape factor' correlation is used to model the heat losses from the side-walls to the substrate. This 'shape factor' correlation has been demonstrated that it works well for a two-dimensional (2-D) dominated heat flow [5]. However, it is not as appropriate for use in a three-dimensional (3-D) heat flow problem. Since the 2-beam thermal actuator has a shuttle connecting the beams (Figure 1), it becomes questionable whether the 'shape factor' correlation is applicable in this situation. To reduce any uncertainty associated with the thermal modeling, this investigation will include the surrounding air in the computational domain and model heat conduction in air explicitly (Figure 2). Hence, the shape factor correlation is not used in the present analysis.

Besides including air computational meshes in this analysis, two different designs of 2-beam thermal actuators have been investigated. The first design has the beams made of three laminated polysilicon structural layers: Poly1, Poly2, and Poly3 layers. The thickness of the air gap between the bottom surfaces of beams and the silicon substrate is about 2 μm. The other design has the beams made of two laminated polysilicon structural layers: Poly3 and Poly4 layers. In this case, the thickness of the air gap between the bottom surfaces of beams and the silicon substrate is about 6.7 μm. The thicker the air gap, the lesser amount of heat will be lost to the silicon substrate.

EXPERIMENT

Surface Raman scattering of laser light has been used to measure temperature profiles along the beam of this 2-beam electro-thermal actuator [4]. The 1.2-μm in-plane resolution of our Raman probe is capable of resolving the 3-μm width of the actuator beams. A detailed uncertainty analysis reveals that the reported Raman-measured temperatures are reliable to within ±10 to 11 K [4]. Measured temperature profiles for five different actuator scenarios were reported [4]. Overall, experimental results show that high-quality, reliable temperature measurement can be obtained. To the best of our knowledge, these were the first reported quantitative and spatially resolved temperature data from working thermal actuators, which will be very useful to validate thermal models so that engineers can optimize the micro-actuator design for best performance.

The temperature profiles reported in this manuscript were taken using the same techniques as though reported by Kearney et al. [4] on surface micromachined actuators fabricated using the .the SUMMiT^{TM} V (Sandia Ultra-planar Multilevel MEMS Technology) process [6]. The SUMMiT-V™ process uses four structural polysilicon layers with a fifth layer as a ground plane. These layers are separated by sacrificial oxide layers that are etched away during the final release step. The two topmost structural layers, Poly3 and Poly4, are nominally 2.25 μm in thickness, while the bottom two, Poly1 and Poly2, are nominally 1.0 μm and 1.25 μm in thickness, respectively. The ground plane, Poly0, is 300 nm in thickness and lies above a 800 nm layer of silicon nitride and a 630 nm layer of SiO_2. The sacrificial oxide layers between the structural layers are each 2.0 μm thick [6].

DESCRIPTION OF CALAGIO CODE

The coupled physics analysis code, Calagio [7], is used to simulate the thermo-mechanical response of the 2-beam micro-actuator. Calagio assumes that the physical phenomena are loosely coupled. This implies that the linearized equations for the electrical, thermal and mechanical phenomena can be solved separately. In this way, the global problem is partitioned into multiple smaller problems that are more tractable. This strategy has the advantages of being simpler, working well in a massively parallel environment, and avoiding the development of an extremely complex code.

The present Calagio code consists of three regions that model different physical phenomena: eCalore for electrostatic analysis, Calore for thermal analysis, and Adagio for quasi-static mechanical analysis. Calore is a parallel heat transfer program built upon the SIERRA finite element framework [7]. Advanced thermal analysis capabilities include anisotropic conduction, enclosure radiation, thermal contact, and chemical reaction. eCalore is the Calore program in a steady state form to solve an electrostatics problem with electrical potential taking the place of temperature as the dependent variable. Adagio, also based on SIERRA framework, is a nonlinear finite element program for use in analyzing the quasi-static deformation of solids. It assumes a quasi-static theory in which material point velocities are retained but time rates of velocities are neglected. Quasi-static equilibrium solution is found using a nonlinear search strategy that includes nonlinear conjugate gradient solvers.

CALAGIO ANALYSIS

A new set of 'high-quality' experiments has been conducted to further investigate the electro-thermal heating of 2-beam micro actuators. This data will be used to assess quantitatively the Calagio code capability to predict electrical, thermal and mechanical responses of electro-thermo-mechanical actuators. Specifically, two different current settings and two different thermal actuator designs have been investigated and the results of model assessment will be discussed in this paper.

Design 1 (P123)

The first thermal actuator design has the main beam made of three laminated structural polysilicon layers: Poly1, Poly2, and Poly3 (Figure 3). The dimension of this beam is as follows: 4 μm wide at the top and bottom, 2 μm wide in the middle, 6.75 μm high and about 300 μm long. The height of the air gap between the bottom surface of the beam and the top surface of the silicon substrate is about 2.0 μm. The shuttle that connects beams at the center is about 10 μm wide, 100 μm long and 6.75 μm high.

One important finding from the present and previous analyses is that the Calagio results are highly dependent on the material properties. The material properties of these polysilicon layers are highly nonlinear and temperature-dependent. Hence to minimize any uncertainty associated with material properties, the most recently measured electrical resistivity of polysilicon layers are used in this analysis [8]. Since the Poly1&2 layers and the Poly3 layer have different electrical resistivities, the Joule heating generation rates between these two layers are somewhat different. The material properties used in these Calagio simulations such as thermal and electrical conductivity and mechanical strength are temperature-dependent.

Figure 4 compares the calculated and measured temperature distribution along the beam for the case in which the applied electrical current is 15 mA. Two different thermal interfacial boundary conditions have been evaluated in this analysis. The first is to set the temperature boundary condition at the beam-air interface and air-substrate interface be continuous. Calagio's result using this boundary condition shows that it underpredicts the peak temperature significantly. If considering the temperature boundary condition across these interfaces is discontinuous and applying the Smoluchowski's expression (Equation 1) [9] to calculate the magnitude of temperature jump at these interfaces, Calagio's prediction compares reasonably well against experiment data. For this simulation, and the accommodation coefficient has been set at 0.8.

$$T_s - T_w = \frac{2-\sigma_T}{\sigma_T} \cdot \frac{2\cdot(\gamma-1)}{\gamma+1} \cdot \frac{R\cdot\mu}{\lambda} \cdot \left(-q_n^{''}\right) \quad \text{Eqn. (1)}$$

Table 1 also lists other comparisons between predictions and measurement such as voltage, maximum temperature, and displacement. The reported measured voltages and displacements are the average value for the two experimental data sets. Again, the Calagio prediction that considers temperature jump at interface using the Smoluchowski's expression agrees reasonably well with the experimental data. The temperature jump condition needs to be considered because the local heat flux at this interface is extremely high, even though the Knudsen number is very small. The thickness of the air gap between the beams and substrate is only 2 μm; hence, the Knudsen number is 0.0325. The calculated thermal conductance at the beam-air interface using the Smoluchowski's expression is very large, but is not infinite. Under most conditions, the temperature jump is negligibly small. However in this case, since the local heat flux is very large because of the very small air gap between the bottom surface of the beam and the silicon substrate, the predicted maximum temperature jump can reach as high as 20 °C. This is a preliminary finding and our calculations are based on the Smoluchowski's temperature jump model which is derived with an assumption that the ideal gas law is valid. More work, both experimentally and computationally, are needed to validate this result.

Figure 5 shows the comparison between predictions and measurement for the case with the applied current of 12 mA. At 12 mA, the peak temperature generated from resistive heating is relatively smaller, about 470 K instead of 650 K. Hence the heat flux is much smaller; this leads to a much smaller temperature jump at the beam-air interface. Figure 6 plots the temperature and displacement profiles calculated by Calagio, respectively. The calculated voltage across the beams for 12 mA is 4.3 V, which compares reasonably well with measurement (Table 2).

Design 2 (P34)

The second thermal actuator design is very similar to the first design, except the main beams are made of the top two structural polysilicon layers, Poly3 and Poly4, laminated together (Figure 7). The dimension of this beam is as follows: 4 μm wide at the top and bottom, 2 μm wide in the middle, 6.5 μm high and about 300 μm long. The height of the air gap between the bottom surface of the beam and the top surface of the silicon substrate is about 6.8 μm. The shuttle that connects beams at the center is about 10 μm wide, 100 μm long and 6.5 μm high.

The Calagio prediction of thermal response for the second design with an applied current of 10 mA and its comparison with experimental data are plotted in Figure 8. The temperature difference between two calculations with different interfacial boundary conditions is only 26.26 K. The difference is smaller because the air gap is larger; hence the heat flux is smaller. In this case, predictions compares well against measurement (Figure 8 and Table 3).

For the case in which the electric current is raised to 12 mA, Calagio underpredicts the peak temperature moderately (Figure 9 and Table 4). In this case, the peak beam temperature is very high, exceeding 700 K.

DISCUSSIONS

Results of the calculated temperature profile from Calagio reveal that when the beam temperature is moderately increased, to about 500K, the temperature distribution across the beam-air interface is probably continuous. The heat flux is moderately large. However, when the temperature increase of the I-beam is very large, to about 650 K, the temperature across the beam-air interface may not be continuous. This implies that the temperature jump effect may not be negligibly small. Under this conditions, using the Smoluchowski's expression may help to improve the Calagio prediction of the beam temperature profile. However more work is definitely needed.

Sensitivity study has also been performed to assess the present results. This includes: (1) modeling the detailed heat conduction in the substrate; (2) extending the air domain to cover much larger region; (3) refining the mesh; and (4) varying the material properties. The findings are similar to what has been discussed in this paper.

CONCLUSIONS

A new set of Calagio analyses has been performed to simulate the thermo-mechanical responses of the 2-beam micro actuators. In these simulations, the surrounding air is included in the computational domain and the conductive heat loss from the beams through air to substrate is modeled by solving the thermal diffusion equation. The specific findings of the present work as follows:

1. The code prediction has been validated and its result compares reasonably well against experimental data.
2. It is necessary to build a computational domain for the surrounding air and solve the diffusion equation for the heat conduction in air because the existing shape factor correlation is not reliable to use due to the 3-D geometric heat transfer effect.
3. Even though the Knudsen number is very small, the temperature distribution across the beam-air interface and the air-substrate interface may not be continuous locally because of the extremely high heat flux at this location. This finding is preliminary and more quantitative direct measurement and detail analysis is needed to validate this finding.

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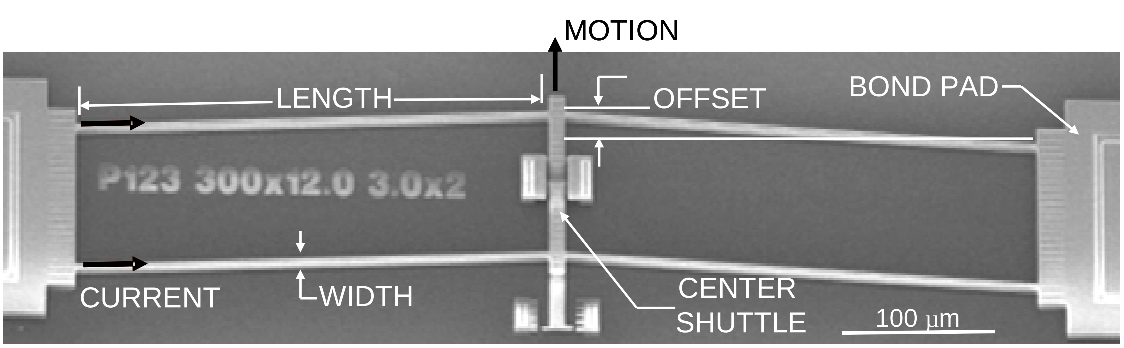

Figure 1: Picture of a 2-Beam Thermal Actuator.

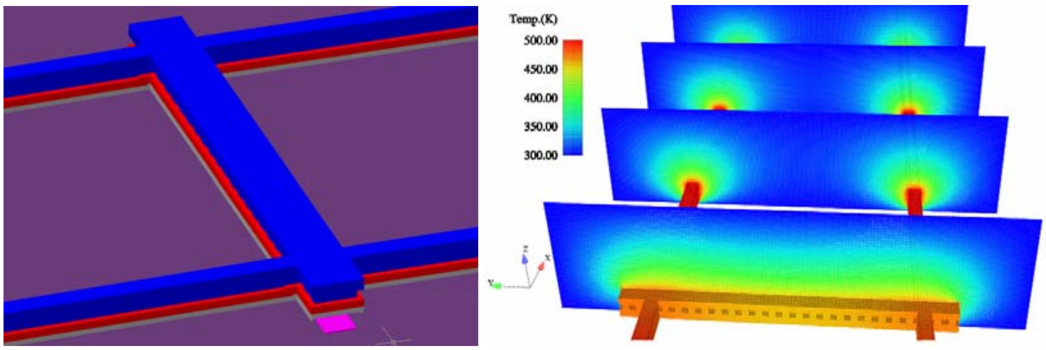

Figure 2: **(Left) 3-D Solid Model of the 2-Beam Thermal Actuator showing the Shuttle at the Center Connecting Beams; (Right) Sequence of 2-D Slap-Shots Showing the Temperature Profile in the Thermal Actuator and Surrounding Air.**

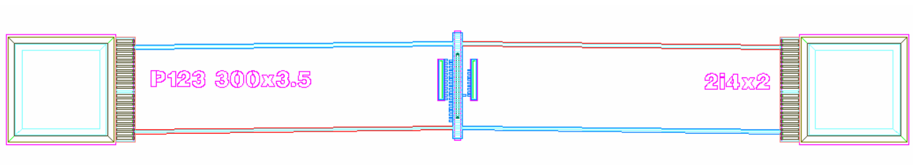

Figure 3: Schematic Drawing of the 2-Beam P123 Thermal Actuator.

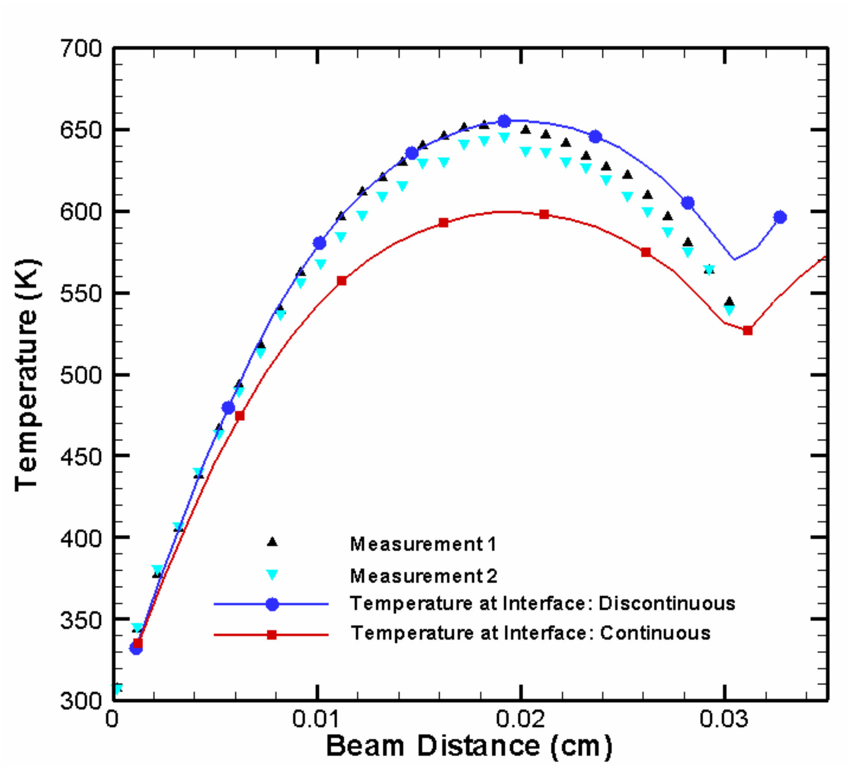

Figure 4: **Comparison of the Calculated and Measured Temperature Distribution along the Beam of a Thermal Actuator. The beam is made of Laminated Poly1, Poly2, and Poly3 (P123) Layers; and the Applied Current is 15 mA.**

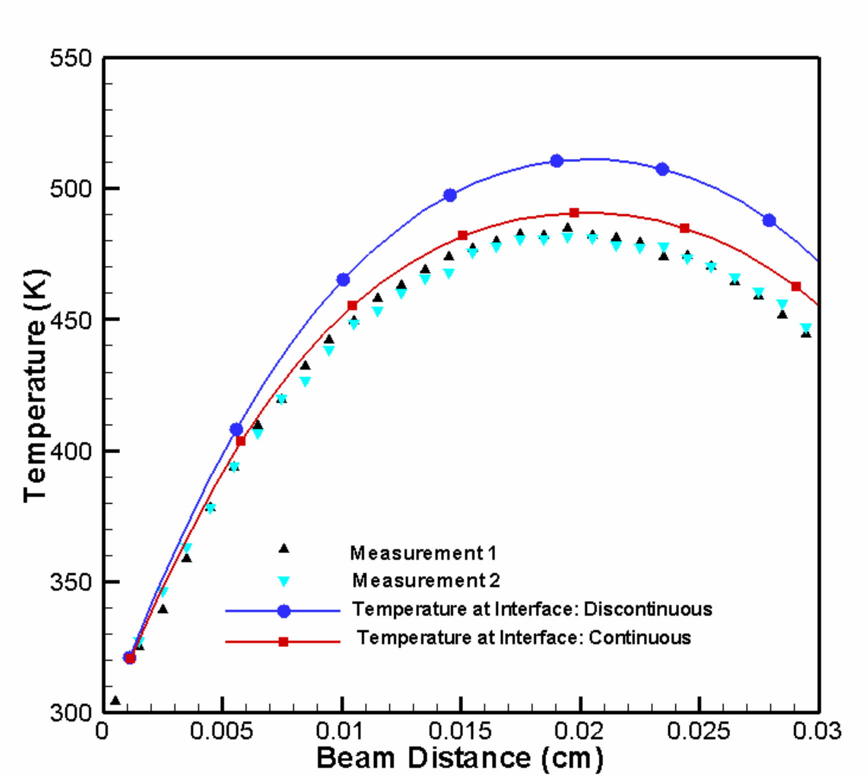

Figure 5: **Comparison of the Calculated and Measured Temperature Distributions along a Beam of the P123 Thermal Acutator; the Applied Current is 12 mA (right).**

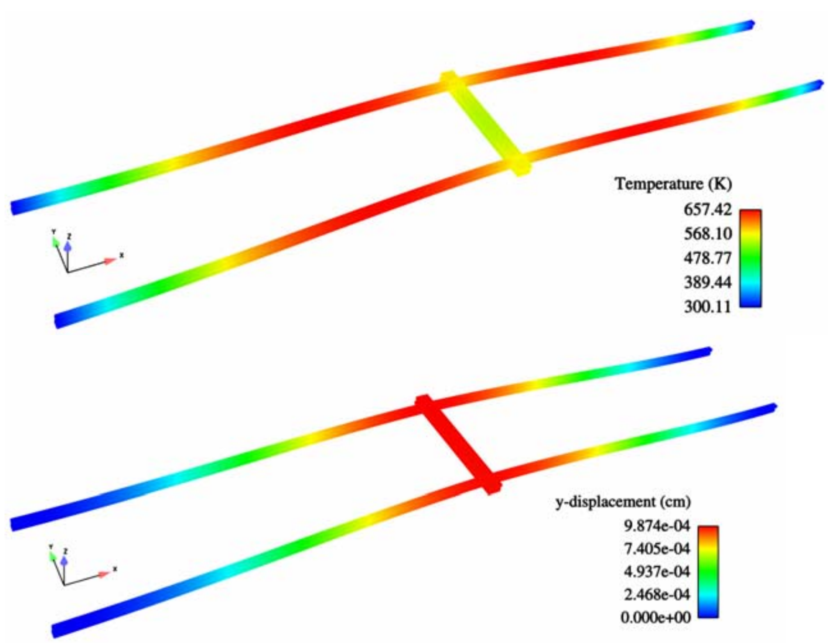

Figure 6: **Calculated Temperature and Displacement Profile of the 2-Beam P123 Thermal Actuator; the Applied Current is 12 mA.**

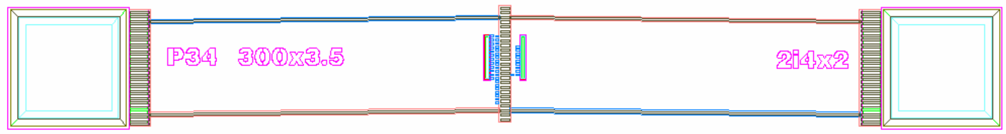

Figure 7 Schematic Drawing of the 2-Beam P34 Thermal Actuator. The Main Beams of this Design are made of the Top 2 Polysilicon Layers.

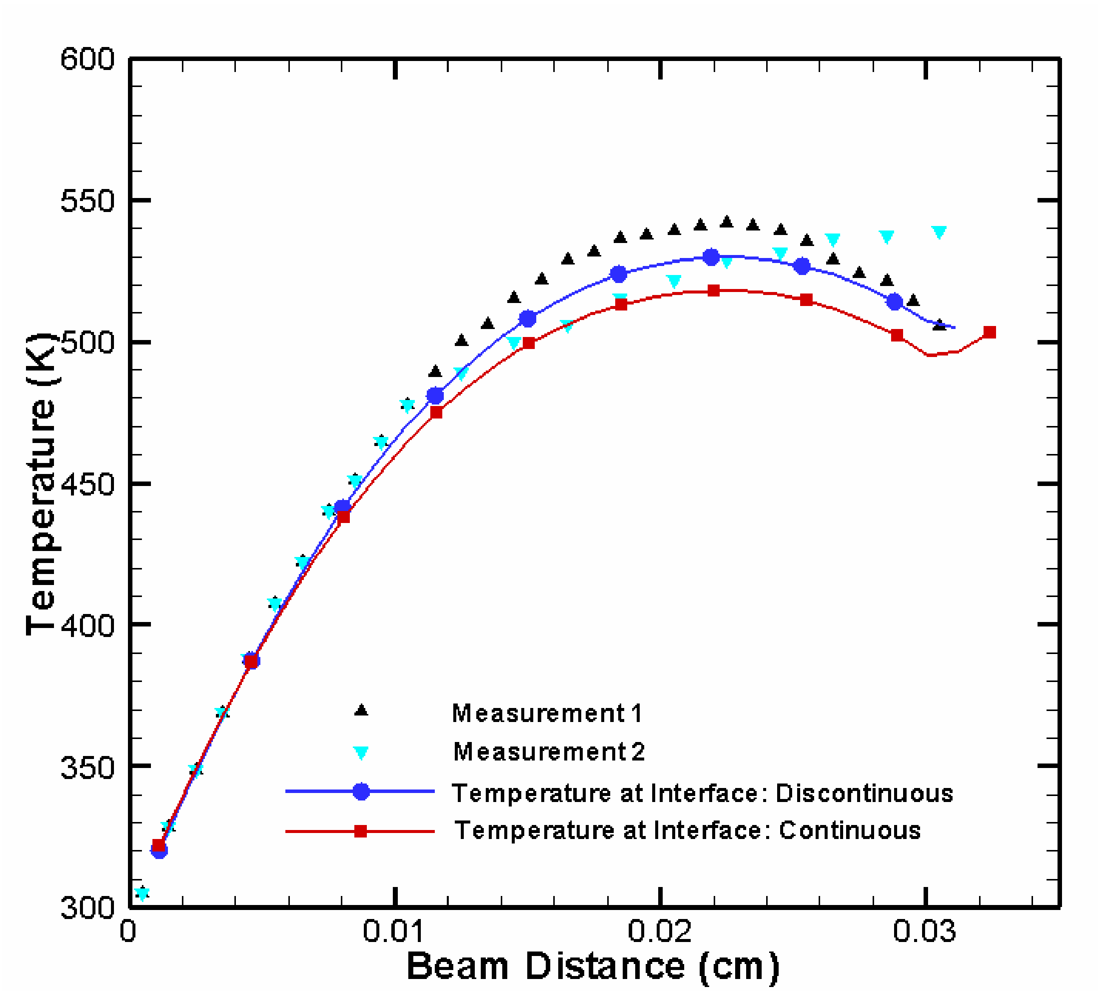

Figure 8 Comparison of the Calculated and Measured Temperature Distribution along the Beam of a Thermal Actuator. The beam is made of Laminated Poly3 and Poly4 Layers; and the Applied Current is 10 mA.

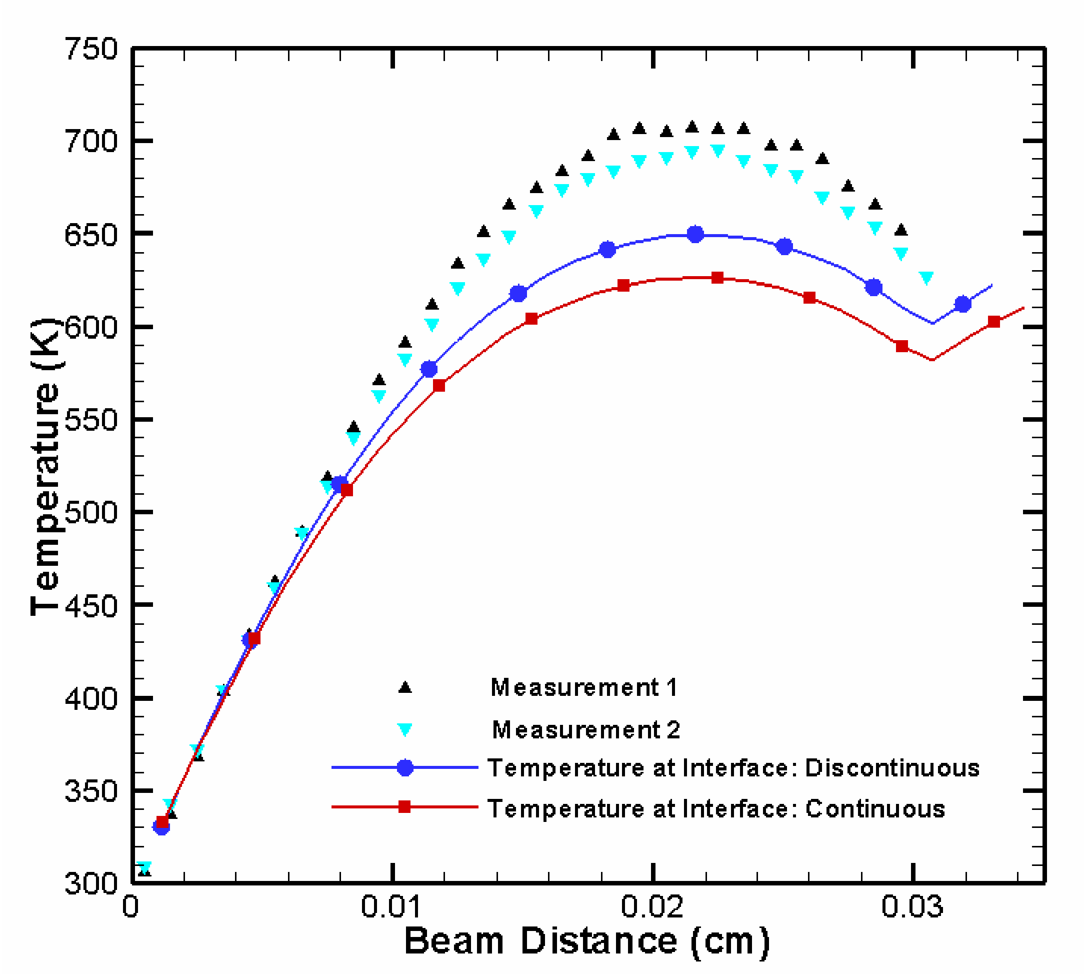

Figure 9 **Comparison of the Calculated and Measured Temperature Distribution along the Beam of a Thermal Actuator. The beam is made of Laminated Poly3 and Poly4 Layers; and the Applied Current is 12 mA.**

	Current	Voltage	Maximum Temperature	Displacement
Measurement	15 mA	5.58 V	649.5 K	9.61 μm
Simulation w/ Discontinuous Temperature at Interface	15 mA	5.76 V	657.4 K	9.87 μm
Simulation w/ Continuous Temperature at Interface	15 mA	5.55 V	599.9 K	8.82 μm

Table 1: **Comparing the Electrical, Thermal, and Mechanical Responses of a 'P123' Actuator with an Applied Current of 15 mA. Predictions with Two Different Boundary Conditions have been Investigated.**

	Current	Voltage	Maximum Temperature	Displacement
Measurement	12 mA	3.89 V	483.1 K	6.67 μm
Simulation w/ Discontinuous Interface Temperature	12 mA	4.15 V	511.8 K	6.84 μm
Simulation w/ Continuous Interface Temperature	12 mA	4.09 V	491.1 K	6.38 μm

Table 2: Comparing the Electrical, Thermal, and Mechanical Responses of a 'P123' Actuator with an Applied Current of 12 mA. Predictions with Two Different Boundary Conditions have been Investigated.

	Current	Voltage	Maximum Temperature	Displacement
Measurement	10 mA	3.81 V	537.5 K	6.67 μm
Simulation w/ Discontinuous Interface Temperature	10 mA	3.66 V	530.8 K	7.22 μm
Simulation w/ Continuous Interface Temperature	10 mA	3.63 V	518.9 K	6.97 μm

Table 3: Comparing the Electrical, Thermal, and Mechanical Responses of a 'P34 Actuator with an Applied Current of 10mA. Predictions with Two Different Boundary Conditions have been Investigated.

	Current	Voltage	Maximum Temperature	Displacement
Measurement	12 mA	5.38 V	700.8 K	9.66 μm
Simulation w/ Discontinuous Interface Temperature	12 mA	4.78 V	651.4 K	9.70 μm
Simulation w/ Continuous Interface Temperature	12 mA	4.71 V	627.9 K	9.28 μm

Table 4: Comparing the Electrical, Thermal, and Mechanical Responses of a 'P34 Actuator with an Applied Current of 12 mA. Predictions with Two Different Boundary Conditions have been investigated.