# Micromachined Thermal Multimorph Actuators Fabricated by Bulk-etched MUMPs Process

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## ABSTRACT

Micromachined thermal multimorph actuators for out-of-plane displacements have been designed and fabricated by Multi-Users MEMS Process (MUMPs) with a post-processing bulk etching step. Micromachined actuators have potential applications in micromanipulation and nanoposition such as manipulation of scanning tunneling microscope (STM) tips, nanopositioner for nano-assembly, micro/nanorobots and cantilever-based nanosensors. The actuator consists of a multilayer micromachined beam constructed of various combinations of polysilicon, oxide and metal layers. The multimorph is heat by applying current to an embedded polysilicon wire to achieve beam bending The maximum tip deflection of 2.5 μm with an input power of 40 mW is achieved. The maximum operating frequency of 2.7 kHz is measured by focus laser reflecting method. A design methodology, device fabrication, and device characterization are presented.

***Keywords:*** Microactuator, Multimorph, MEMS, MUMPs, nanopositioner, Scanning Tunneling Microscope

## 1. INTRODUCTION

Microactuators found many applications in nanotechnology such as nanopositioner and nanoassembly. Presently, microactuators have been used in various applications such as micropump, microvalves, relays, switches, microrobots, and micro-optical elements etc [1]. Different principles such as electrostatic, piezoelectric, electromagnetic and thermal have been used in the microactuators. But thermal actuators are usually simpler, more reliable and easier to construct. Thermal actuation is generally based on either the linear/volume expansion or phase transformation of the materials [2]. The thermal actuators can exhibit large forces and good linearity relative to input power. Compared to electrostatic actuator, however, disadvantages of thermal actuators include high power requirements and lower bandwidths as a result of thermal time constant [1]. But the power consumption and thermal loss can be reduced through elaborated geometric and structural designs of the device and appropriate choice of materials, which can enhance the efficiency of thermal actuators.

The thermal actuators can be categorized based on their motion as in-plane and out-of-plane thermal actuators. In-plane thermal actuator consists of one layer of material with two arms. One arm that has a higher resistance and more power are dissipated as heat, is narrower than the other arm. This causes the bending motion in the direction parallel to the substrate [3,4]. Meanwhile, the out-of-plane thermal actuator mostly bases on bimorph effects and consists of two layer of material with different coefficient of thermal expansion (CTE) The bimorph beam will bend due to mismatch of CTE of various layers when there is temperature variation on the actuators. Out-of plane thermal actuators based on bimorph effects have been demonstrated by Baltes et al. [5] and Riethmuller and Benecke [6]. In previous work, thermal actuators were fabricated by a CMOS process [7]. In this paper, we present design, model, fabrication, and performance test of a micromachined thermal multimorph actuators fabricated by standard surface micromachining foundry called Multi-Users MUMPs Process (MUMPs) with a post-processing bulk-etching step [8].

## 2. DEVICE DESIGN

Figure 1 shows the tested thermal multimorph actuators with various material combination. All actuators have the identical geometry of 15 μm wide and 100 μm long with U-shape polysilicon heating wire of 3 μm wide and 200 μm long.

The actuators are designed with a combination of polysilicon and silicondioxide ($SiO_2$) layers with the top metal layer. The thermal actuator consists of a polysilicon resistor encapsulated in $SiO_2$ and a gold layer as shown in Fig. 2. Due to the different coefficients of thermal expansion of multi-layer sandwich of different materials, the actuator flexure curl when ohmic heating is generated by applying electrical power to the resisters, thus causing the high-resolution deflection of actuator tip. The achieved tip displacement is a function of the actuator design parameters, such as beam length, layer thickness and beam material composition.

An array of actuators is designed for performance test. The 12 actuators as shown in Figure 1 has been fabricated using different combinations of layers available in MUMPs as listed in Table.1.

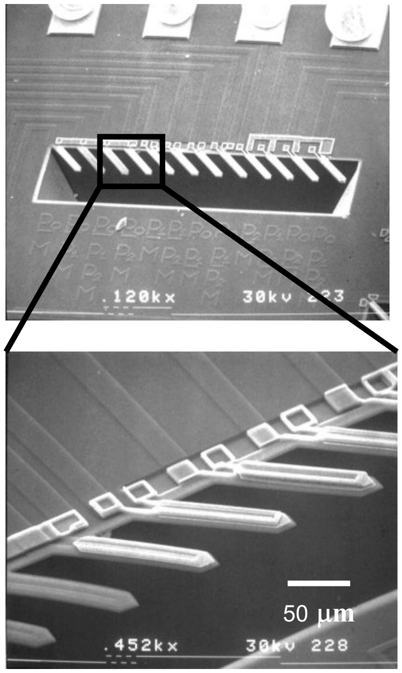


Figure 1: Array of thermal multimorph actuators with various material combinations.

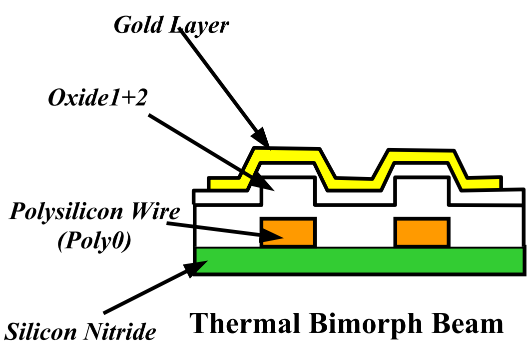


Figure 2: The cross section of the thermal bimorph actuator.

| Beam | Layer Combination | Beam | Layer Combination |
|---|---|---|---|
| 1 | *P0*, M | 7 | P0, *P1*, M |
| 2 | *P0*, P1, M | 8 | P0, *P1,* P2, M |
| 3 | *P0*, P1, P2, M | 9 | *P2*, M |
| 4 | *P0*, P2, M | 10 | P1, *P2*, M |
| 5 | *P1*, M | 11 | P0, *P2*, M |
| 6 | *P1*, P2, M | 12 | P0, P1, *P2*, M |

where *P0*, *P1*, *P2* is Poly0, Poly1, Poly2 respectively, and *M* is Metal. The italic layer is used as a heating wire.

Table 1: Combination layer of thermal multimorph actuators available through MUMPs.

## 3. DESIGN MODELING

Multimorph beams consist of layers of material sandwiched together to form a composite beam. In case where there are only two layers, the beam is called a bimorph. Since the thickness of the heating resistor is small compared to the thickness of the encapsulated oxide, the thermal actuation can be simply modeled as a bimorph [9]. The tip displacement for each type of actuators is a function of temperature and beam material composition. The material properties for each layer are assumed to be uniform throughout the layer and constant with temperature and no internal friction between the bimorph layers. The temperature distribution within the beam is assumed to be uniform since an embedded heating resistor that span the entire length of the beam is typically used for heating. The relationship between tip deflection *d* of the bimorph actuator and temperature variation is given by [10]:

$$d = \frac{kL^2}{2} = \frac{3}{4}L^2 \frac{\Delta T}{t_1 + t_2} \frac{\alpha_2 - \alpha_1}{1 + \frac{\left(E_1 t_1^2 - E_2 t_2^2\right)^2}{4E_1 t_1 E_2 t_2 (t_1 + t_2)^2}} \qquad (1)$$

where $r$ is radius of curvature $=1/k$, $k$ is the beam curvature, $L$ is the beam length, $\alpha_1$ and $\alpha_2$ are the CTEs of two bimorph layers, $E_1$ and $E_2$ are their Young's modulus, $t_1$ and $t_2$ are their thickness, and $\Delta T$ is the temperature difference between the operating and initial temperatures. For a bimorph actuator, the force generated is distributed linearly along the beam length. From the beam theory, the force $F_d$ generated at the end of the tip deflection $d$ is given by [11]:

$$F_d = \frac{3EId}{L^3} \qquad (2)$$

where $EI$ is the flexural rigidity of the composite beam. Since the bimorph beam consists of two materials, the neutral axis of the beam may no longer in the middle of the beam cross-section. Either composite beam or transformed-section method must be use to calculate the flexural rigidity $EI$ of the bimorph beams.

The commercial finite element package MARC with MENTAT was used to perform the analysis. The modeling consisted of an electro-thermal analysis to obtain the temperature distribution resulting from an input current as shown in Fig. 3. This was then coupled to a mechanical analysis in which the temperature distribution was used to determine the static deflections resulting from thermal expansion mismatch.

## 4. DEVICE FABRICATION

Micromachined thermal multimorph actuators have been fabricated through commercially available Multi-User MEMS Process (MUMPs) [12].

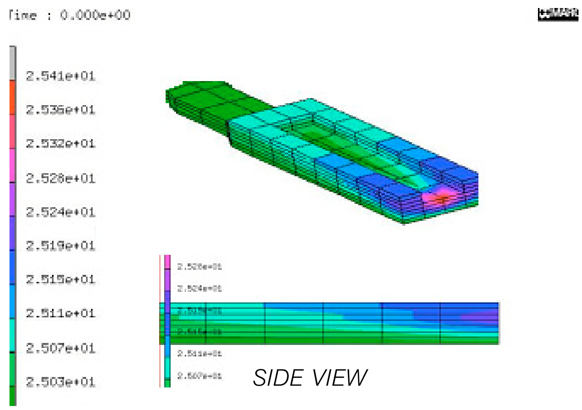


Figure 3: Thermal distribution in a multimorph beam when current is applied and its side view.

To suspend multimorph microactuators over cavities, the bare single-crystal silicon substrate is exposed to chemical etchant using the superimposition of "Anchor1", "Anchor2", Poly1-poly2 via", "Dimple", "Hole1" and "Hole2" layers on top of each other as shown in Fig. 4.

By this method, the nitride and all the oxide layers above nitride are opened through during regular MUMPs fabrication, leaving exposed bare silicon while the other area of the chip is covered with oxide and nitride layers [8]. The silicon substrate is anisotropically etched by EDP or KOH etchant or isotropically etching by xenon difluoride ($XeF_2$). The polysilicon structures are not effected by EDP etching because the etching rate of polysilicon in these chemical etchant is much slower than single-crystal silicon and can be negligible. By this method, the surface and bulk micromachining can be done and integrated on the same chip with only a maskless post-processing step required on MUMPs chip.

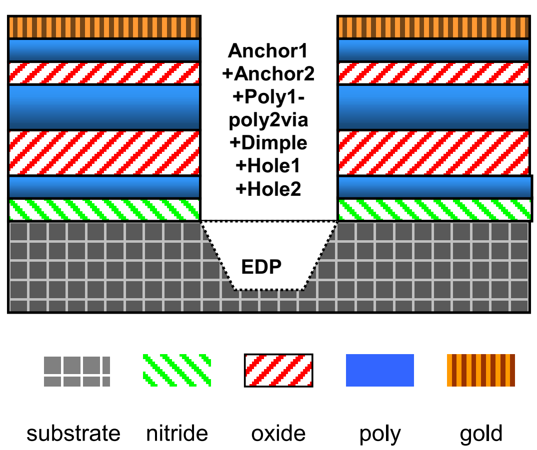


Figure 4: Schematic diagram of MUMPs and "cut through substrate" mask for bulk etching post-processing step with EDP.

## 5. DEVICE CHARACTERIZATION

Static deflections of the actuators are measured over a range of input powers using a Zygo interferometric microscope. When the beam is actuated, the tip of actuator bends downward with different amount of deflection depending on each beam structures. The profile of actuated beam is shown in Fig. 5. Figure 6 shows the experimental plot of the actuator deflection as a function of input power. Thermal actuator beam #1 has a largest deflection compared to the other beams because this beam is the thinnest beam with thickness of 3.87 µm consisted of the layer of Oxide1 and Oxide2 between gold and Poly0 wire. Thus the spring constant is the lowest compared to the other beams. And with the thermal expansion coefficient mismatch between silicon dioxide and gold layer of 40:1 (CTE of gold is 14.2 ppm/K and CTE of $SiO_2$ is 0.35 ppm/K), the maximum deflection of 2.5 µm is achieved using *P0*M actuator (beam #1). Focused laser reflecting test setup is used to determine the dynamic behavior of the actuators. Laser beam is focused onto the tip of actuator and reflected to a photodetector to detect the frequency of an operating actuator. Rise time and fall time of reflected signal is measured to determine the minimum cycle time of the actuators. The rise time is measured as 150 µs and fall time is 220 µs, thus minimum thermal time constant or the time required to completely heat and cool is 0.37 ms. Therefore, the maximum operating frequency of the actuators is 2.7 kHz when the actuators are driven by a square wave as shown in Fig. 7.

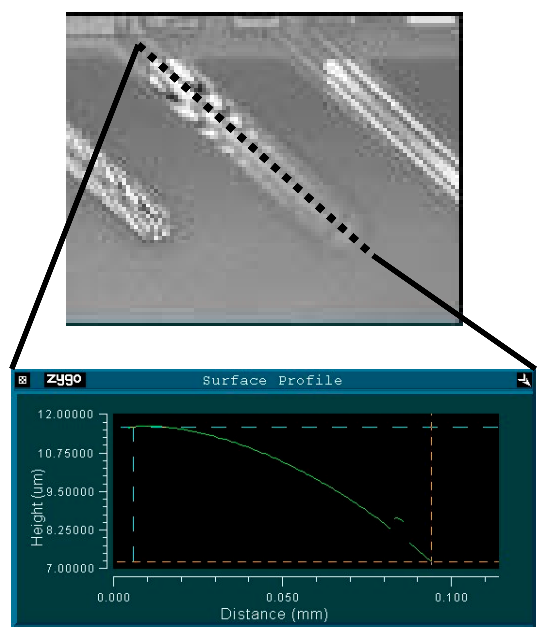


Figure 5: Actuator deflection measurement using white light interferometric microscope.

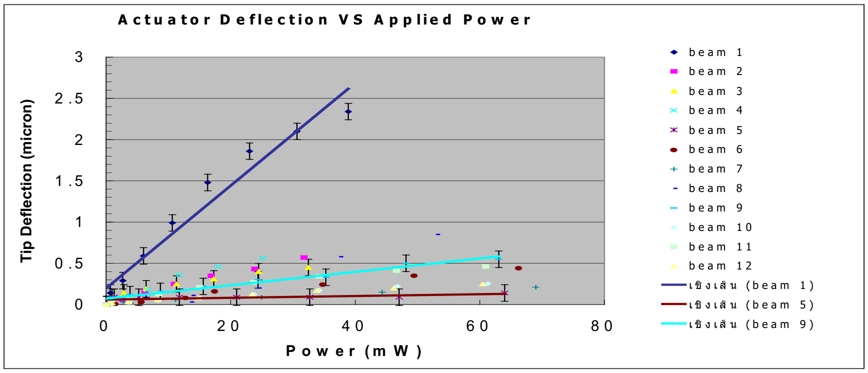


Figure 6: Measured actuator deflection versus applied power.

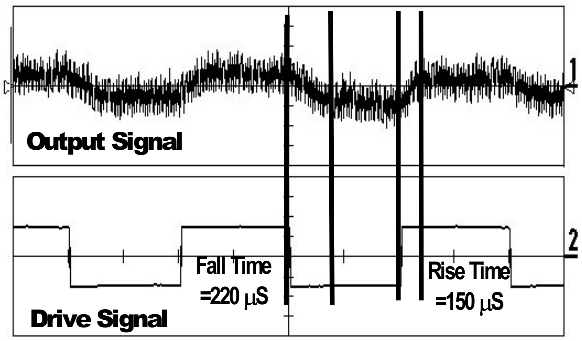


Figure 7: The operating frequency measurement of *P0*M actuator.

## 6. CONCLUSIONS

We present a thermal multimorph microactuator based on MEMS technology. The actuator is fabricated by standard MEMS foundry with additional post processing step of substrate etching. A design methodology used various combinations of available layers to determine the best actuator with a largest deflection is presented. Device characterization on both static and dynamic behaviors is experimentally determined. The maximum deflection of 2.5 µm with maximum operating frequency of 2.7 kHz is achieved. Micromachined thermal multimorph actuators found many useful applications such as microactuators in microrobotics and micromanipulators in a precise assembly. The use of these actuators in various applications is in study.

## 7. ACKNOWLEDGEMENT

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