Three degrees of Freedom Thermal Microactuator

A. Pasupuleti, F. Sahin, W. W. Walter, A. Raisanen, J. L. Hebding and K.Hirschman

Rochester Institute of Technology, Microsystems Engineering
79 Lomb Memorial Drive, Rochester, New York, USA, axp1014@rit.edu

ABSTRACT

A novel thermal actuator has been designed and fabricated. The proposed microstructure has three degrees of freedom and as such can have displacements simultaneously in the X, Y and Z-axis. The operation of the microactuator is based on thermal expansion of polyimide. The displacement in the three axes is obtained by placing individually controllable heaters on the polyimide surface such that they produce localized expansion. The performance of the microactuator was evaluated by using the physical properties of materials and finite element analysis (FEA) using ANSYS software. The effects of shape, size, and the material properties of the actuator as well as the heater elements were analyzed and optimal designs were derived. The fabrication process sequence was detailed.

Keywords: thermal actuator, three degrees of freedom, polyimide, Ansys simulation, fabrication.

1 INTRODUCTION

Micro Electromechanical Systems (MEMS) is a field that is in a state of rapid expansion in both the academic and the industrial world. Over the last decade, the size of MEMS devices, mainly actuators, have been reduced from millimeters to micrometers. This advancement is associated with the development of various high aspect ratio fabrication techniques; both in bulk and surface micromachined processes, and to its wide spread applications [1 - 3]. MEMS devices are foreseen to be very useful in applications that require flexibility, adaptability and accessibility [2]. Examples of some such applications are fixing failures in pipes used in power plants [1, 2], for gene manipulation and cellular fusion in the field of medicine [2, 4]. In all these applications existing equipment fails as it is often bulky and results in the loss of flexibility and resolution at such a small scale of operation [2]. Other applications for MEMS devices are in the field of micro-optics and high-speed communication networks [5]. In all the above-mentioned applications, the actuator having a controlled large out-of-plane deflection achieves the desired task.

In the literature, many structures have been fabricated that produce large deflections using different kinds of actuation techniques [6]. These microstructures can be broadly classified into two categories, based on the degrees of freedom (DOF) of the moving part of the actuator. They are one DOF and two DOF microstructures. In the one DOF microstructures, the moving part is restricted only to one direction of movement. Examples of this kind of actuator include the comb drive that produces transverse displacement and the self deformed bilayer cantilevers that produce out-of-plane displacement [7, 8]. On the other hand, in two DOF microstructures the moving part of the actuator is capable of having displacement in two directions. Examples of such devices are the bistable microactuators [6, 9]. Due to the added degree of freedom, two DOF actuators have more flexibility when compared to the one DOF actuators. However, in applications such as microrobotics, two DOF actuators restrict the movement of the actuator to straight paths. This could result in the microrobot having a large turning radius, resulting in more power consumption and less stability during turns [10]. In surgical applications, microprobes that have multi degrees of freedom are in great demand so that surgeons can perform low risk, real time operations [4]. To meet these requirements, we have designed a microactuator that has three degrees of freedom and is capable of producing large deflections.

This paper is organized as follows. In section 2 the proposed microstructure is described. Section 3 describes design and modeling aspects that have been performed using finite element analysis. Section 4 describes the fabrication process sequence for realizing the proposed designs. Section 5 describes the simulation as well as the experimental results, followed by conclusions and suggested future work in section 6.

2 PROPOSED MICROACTUATOR

This research is focused on the design and fabrication of a novel MEMS device that has three-degrees-of-freedom and is a polyimide-based thermal microactuator. The proposed actuator can have displacements simultaneously in the X, Y and Z-axis. The operation of the microactuator is based on thermal expansion of polyimide. The displacement in the three axes is obtained by placing individually controllable heaters on the polyimide surface such that they produce localized expansion. Figure 1 illustrates the schematic of the proposed microactuator. This microstructure consists of a suspended glass beam with a large groove that is filled with polyimide. Heaters are placed on top as well as bottom of polyimide.

In previous work it has been shown that polyimide joint techniques have produced well-controlled out-of-plane rotations [6]. The thermal shrinkage of polyimide occurs in two modes that are static and dynamic. While the static mode is a result of the polyimide shrinkage in the curing process that results in a static bending angle, the dynamic mode determines the motion of the microactuator. The dynamic mode is a function of the thermal expansion coefficient (CTE). For a given temperature, materials that have higher CTE values expand more than those that have low CTE values. This difference in expansion results in the deflection of the microstructure. Controlled deflection can be achieved by regulating the amount of heat applied to the actuating material while keeping in mind that the maximum deflection obtained is limited by the material properties. Since cured polyimide has high CTE value, it makes a very good actuating material and shall be used in the proposed microactuator [6].

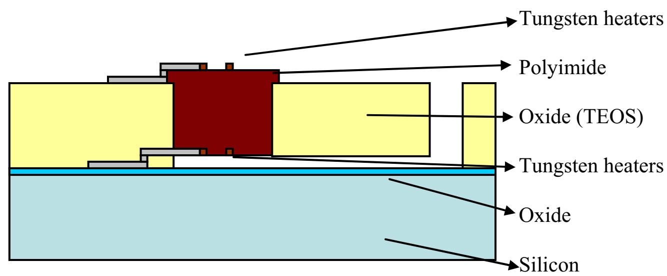


Figure 1: Schematic of the proposed thermal microactuator

3 MODELING

In this analysis, emphasis is placed on the dynamic actuation mode. From the above discussion it is clear that dynamic actuation is dependent on the thermal expansion coefficient and the temperature gradient in the actuating material [6]. As CTE is characteristic to a material, the only other major factor that affects the performance of the microactuator is the temperature gradient. In the proposed microactuator the temperature gradient is produced with the help of external heaters. As a result, the performance of the microactuator is a function of the material properties as well as the dimensions of the heaters.

Simulations were performed to study the effect of type and shape of the heaters on the performance of the device. Two different types of materials were considered, aluminum and tungsten. The effect of the shape of the heaters was studied using square, vertical strip and horizontal strip heaters. Ansys® a finite element analysis software tool was used to model the above behavior [11]. In this software, simulations were performed in the structural analysis mode with boundary conditions applied in the displacement and temperature environments. A two-dimensional analysis was performed to study the effect of different types of heaters and a three-dimensional analyses was used to study the effect of the shape of the heaters. Plane 42 and solid 95 predefined Ansys® elements were used to perform two-dimensional and three-dimensional analyses respectively. In these simulations, bulk properties for the elastic modulus, poison's ratio and the CTE were used for all the materials. The solution was computed using non-linear steady state static analysis with the convergence dictated by the Newton- Raphson method.

4 FABRICATION

The fabrication of the microstructure uses standard semiconductor fabrication techniques. The structure is fabricated using thin-film surface micromachining, with a sacrificial release layer freeing the device. The following outline and cross-sections detail the fabrication of the device.

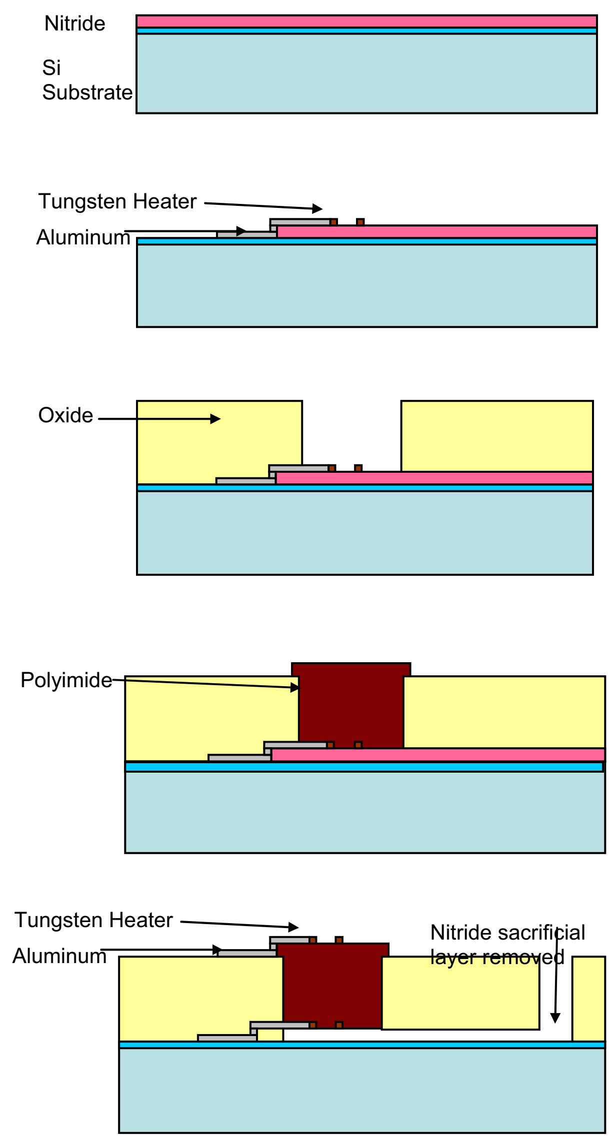


Figure 2: Cross-sections illustrating fabrication of the proposed device.

- Thermal oxide is grown as a stress-relief layer.
- CVD nitride is deposited and patterned as the sacrificial release layer.
- Tungsten is deposited and patterned to form the bottom heaters.
- Aluminum for the bottom heater interconnects is deposited and patterned.
- A thick PECVD TEOS oxide is deposited to form the structure of the device.
- An oxide trench is etched completely to the sacrificial layer, over the bottom heaters.
- Polyimide is spun coat to fill the trench.
- A second tungsten deposition and pattern forms the top heaters.
- Aluminum is deposited, and patterned to allow definition of the cantilever.
- A second definition of the aluminum defines the top heater interconnects.
- The sacrificial nitride is etched, releasing the structure.

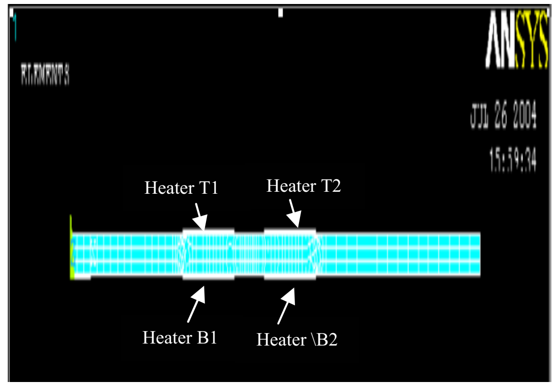
5 RESULTS AND DISCUSSION

Figures 3a and 3b illustrate the proposed microstructure as defined in Ansys®. As described in section 2, the proposed structure was made up of a cantilever beam with polyimide sandwiched in between two glass (TEOS) pieces. The three components of the cantilever beam are identified with TEOS1, P, and TEOS2 which represent the glass piece that was connected to the substrate, polyimide and the second glass piece, respectively. Metal heaters were deposited on top and bottom of the polyimide section which were represented by T1 and T2 (Top heaters), and B1 and B2 (bottom heaters).

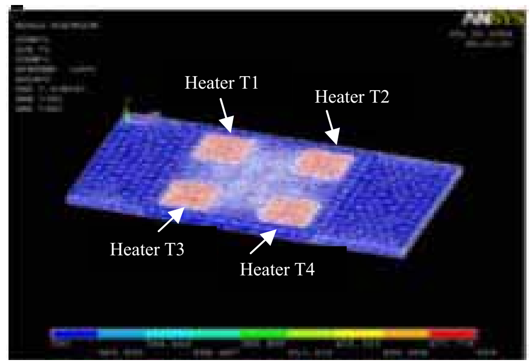
Table 1 illustrates the 2D simulation results for cumulative deflection of the microstructure obtained by using different type of heaters that are heated to 500K from room temperature. The dimensions of the cantilever beam are TEOS1 (20µmX5µm), P (50µmX5µm), TEOS2 (30µmX5µm) and heaters were 10µmX0.05µm. Results in this table indicate that the deflections produced by tungsten and aluminum heaters are comparable. Thus due to fabrication considerations, this process selected tungsten heaters.

Table 1: 2D simulations for different heating material

NO	Heater (On = 1) 1	2	3	4	Temp K	Deflection (µm) W	Al
1	1	1	1	1	500	0.004	0.005
2	1	1	1	0	500	0.033	0.053
3	0	1	1	1	500	0.058	0.09
4	1	1	0	0	500	0.092	0.144



(a)



(b)

Figure 3: Schematic of the proposed micoactuator with (a) strip heater and (b) square heater

The effect of the shape of the heaters was analyzed using 3D Ansys® simulations. Table 2 illustrates the results for some of the heater configurations for different tungsten heater shapes that have the same area and thickness. The dimensions of the cantilever beam are TEOS1 (25µmX60µmX3µm), P (50µmX60µmX5µm), TEOS2 (30µmX60µmX5µm) and heaters had an area of 256µm^2. Strip heaters were arranged in two different directions. X and Z strip heaters are heaters that are parallel and perpendicular to the length of the cantilever respectively. In this table, the heater configurations are illustrated by indicating the heater name. For example, T1 T2 T3 T4 indicates that all the top heaters are assumed to be switched on. These results indicate that the strip heaters produce more deflection when compared to the square heaters in the X and Y directions. However, square heaters produce more deflection in the Z-axis. As a result, the orientation of the heaters is application dependent. Simulations indicate that having different shapes for the top and bottom heaters result in large deflections in all three directions. One must note that these simulations were performed for cantilever beams with a very small TEOS2 section. These results can be magnified by a large extent by increasing the length of the cantilever beam as illustrated by the experimental data in [12].

Table 2: 3D simulations for different heater shapes

Heater shape	Temp (K)	Configuration	Deflection (µm) UX	UY	UZ
Square	500	T1 T2 T3 T4	0.01	0.347	0.008
		T1 T2	0.01	0.177	0.01
		T3 T4 B3 B4	0.019	0.020	0.01
X-strip	500	T1 T2 T3 T4	0.02	0.56	0.004
		T1 T2	0.01	0.29	0.01
		T3 T4 B3 B4	0.008	0.067	0.001
Z-strip	500	T1 T2 T3 T4	0.01	0.19	0.014
		T1 T2	0.002	0.12	0.013
		T3 T4 B3 B4	0.006	0.002	0.012

A recent study conducted by the authors in characterizing the mechanical behavior of micromachined cantilevers revealed that the material properties of thin films deviate substantially from their bulk values [12]. Experimental results for bilayer cantilevers indicated large out of plane rotations, which were otherwise not predicted by simulations that used bulk material properties [12]. This research indicates a possibility that the dynamic deflections obtained by the proposed actuator may be a conservative estimate of the actual values.

6 CONCLUSIONS AND FUTURE WORK

A novel microactuator that has three degrees of freedom was proposed and simulated. The proposed actuator was actuated by polyimide based thermal actuation technique. Simulation results indicate that the material properties as well as the shape of the external heaters play a critical role in the performance of the actuator. Efforts have been made to verify the simulation results with experimental values. To this effect the fabrication process sequence has been identified and discussed. Research is in progress in developing empirical models for polyimide using the methodology described in [12] which should be later utilized to estimate the deflections of the proposed actuator.

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