Investigation of Vertical Displacement Thermal Actuators

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ABSTRACT

In this paper, we present design, modeling, fabrication, testing techniques and experimental verification for a bi-directional thermal actuator. The actuation principle is based on the asymmetrical thermal expansion of pseudo-bimorph microstructures due to the difference in the electrical resistance of two stacked poly-silicon layers. Bi-directional actuation is achieved depending upon the application of currents on either the top or bottom layers. Various designs were fabricated using the commercial foundry process PolyMUMPS and characterized with a reflective microscope and an optical profiler. Previous demonstrated designs had a limited vertical displacement due to the mechanical limitation imposed by the flexural lengths of the actuator arms. We proposed a new design allowing an increase of the maximum displacement by 85% with the same input voltage of 7V. The flexure arm is incorporated in the top silicon layer such that the torsion forces on the flexural arms are minimized. This enables larger deflection of the actuator arm without significant increase in the temperature. Different device configurations have been designed and tested. The temperature distributions on the actuator arms and displacements of the actuators at various conditions were analyzed using finite-element analysis and verified experimentally. We will discuss the design configuration, testing techniques and practical issues. The potential applications of the out-of-plane actuators include flow sensors, variable capacitors, resistive sensors, optical switches and RF switches.

Key words: Thermal actuator, out-of-plane actuator, bi-directional actuation.

1. INTRODUCTION

The fields of MEMS (micro-electro-mechanical systems) and optical microsystems are at a fast growing stage. Optical MEMS has become a promising technology in the fields of telecommunication, high-resolution display, and medical imaging. Various actuation mechanisms have been used to actuate the micro optical devices such as electromagnetic, electrostatic, and piezoelectric actuation [1-3]. The thermal actuator can provide larger deflection and higher force [4]. It can be fabricated using cost effective conventional semiconductor processes such as SOI (silicon on insulator), bulk micromachining and surface micromachining.

The actuation principle of thermal actuator is based on the asymmetrical thermal expansion of pseudo-bimorph microstructures due to the difference in the electrical resistance of two stacked poly-silicon layers. Bi-directional actuation is achieved depending upon the application of currents on either the top or bottom layers.

2. DESIGN

A typical in-plane thermal actuator consists of a hot arm and a cold arm [5]. The hot arm being thinner than the cold arm, has higher electrical resistance, and therefore provides higher temperature when electrical current is applied. Consequently, the hot arm expands more than the cold arm due to difference in thermal expansion resulting in the actuation mechanism. The out-of-plane thermal actuator is similar to the work done by Yen *et al* [4]. This design is a modified design of [6] to provide a bi-directional actuation mechanism.

A 3-D view of the vertical thermal actuator is shown in Fig. 1. The actuator consists of two polysilicon layers mechanically connected to each other at one end through via, and anchored to the substrate at the other ends where

electrical current can be applied. The *Arm 1* in Fig. 2 represents the flexure length of the device. The actuation principle of the vertical thermal actuator is similar to that in [4] as the deflection of the actuator tip is due to the difference in thermal expansion of the hot and cold arms. The bi-directional actuation is achieved depending upon the application of electric current on specific electrodes. If the current is applied on the contact pads 1 and 2 in Fig. 1, the deflection is upward because the current only pass through the bottom layer which expands due to the increase in temperature, whereas if electrical current is applied on the contact pads 3 and 4, the deflection is downward

Figure 1 3-D view of a bidirectional vertical thermal actuator.

Figure 2 One dimensional representation of the thermal actuator [4].

3. LUMPED MODELING ANALYSIS

The lumped modeling analysis is based on the work done by Yen *et al.* [4, 5]. Assuming the heat loss due to radiation is negligible, the analysis is performed as a one-dimensional heat transfer problem. The temperature distribution along the length of top or bottom layer of the actuator is

$$T_i = T_s + \frac{B_i}{A_i^2} + C_i e^{A_i x} + C_i' e^{-A_i x} \quad (1)$$

where i (=1, 2, and 3) represent the number of arm of either the top or bottom layer of one dimensional model as shown in Fig. 2. The parameters are:

$$A_1 = \sqrt{\frac{S_1}{k_p R_1 t_{p2}}} + B_1 \xi, \quad A_2 = \sqrt{\frac{S_2}{k_p R_2 t_{p2}}} + B_2 \xi, \quad A_3 = \sqrt{\frac{S_3 w_2}{k_p R_3 A_v}} + B_3 \xi \quad (3)$$

$$B_1 = \frac{V_1^2}{L_1^2 \rho_0 k_p}, \quad B_2 = \frac{V_2^2}{L_2^2 \rho_0 k_p}, \quad B_3 = \frac{V_3^2 A_v}{L_3^2 \rho_0 k_p A_c} \quad (4)$$

$$V_1 = \frac{V}{2(L_1 + L_2) + L_3} L_1, \quad V_2 = \frac{V}{2(L_1 + L_2) + L_3} L_2, \quad V_3 = \frac{V}{2(L_1 + L_2) + L_3} L_3 \quad (5)$$

where S_i is the shape factor of the arm i , R_i is the thermal resistance between the arm i and the substrate, ξ is the linear temperature coefficient, t_{p2} is the thickness of top layer, and V is the voltage applied on the contact pad.

The temperature distribution along the bottom layer of the thermal actuator can be calculated using Eq. 1–4 and a series of equations given in [4]. The temperature distribution at an input voltage of 5 V is shown in Fig. 3. Since a lumped model was assumed in the analysis, three separate curves were obtained for each of the three arms of the thermal

actuator (the blue curves in Fig. 3). A polynomial curve, shown in the red color, shows the actual temperature distribution along the layer. It can be seen from the figure that the temperature distribution is symmetrical about the center. Similarly, the actuator tip deflection can be obtained by using linear thermal expansions of the top and bottom layers as an input to the mechanical analysis. Mechanical analysis similar to [4] can be performed to obtain the total tip deflection of the thermal actuator.

A maximum tip deflection of $6.2 \mu\text{m}$ at an input voltage of 7 V was reported by Yen *et al.*[4]. We modified and optimized the flexure design to increase the deflection. We achieved an average tip deflection of $11.5 \mu\text{m}$ at an input voltage of 7 V which is approximately 85% increase in total displacement. In this design, the flexure length is $20 \mu\text{m}$ with a length L_2 of $217 \mu\text{m}$. The higher deflection of the actuator can be achieved without significant increase in the actuator body temperature.

Figure 3 Temperature distributions along the bottom layer of the thermal actuator.

Figure 4 Temperature distributions along the top layer of the thermal actuator.

4. FINITE ELEMENT ANALYSIS

Finite element analysis was used to validate the temperature distribution along the top and bottom layers, and actuator deflection. The actuator model was built using *SolidWorks* and imported to *Ansys*. A couple field element called "Scalar Tet 98" in *Ansys* was used for the simulation. Three boundary conditions were applied to the model. Thermal boundary condition was applied by keeping the actuator at an initial temperature of 27°C . Electrical boundary condition was applied by an input voltage. Mechanical boundary condition was applied by applying zero degree of freedom on the contact pads.

First, the model provided in [4] was simulated to verify our simulation procedure. The simulation result is shown in Fig. 4 at an input voltage of 5 V . The maximum temperature of the top layer obtained from the simulation is 731.56°K which is close to the temperature of 695.36°K reported by [4]. The electrical parameters used for this simulation are obtained from the *MatWeb* database [7] as shown in Table 1. The difference in temperatures may be due to the difference in electrical parameters.

Table 1. Material properties of polysilicon.

Material Properties of Polysilicon	Value
Young's Modulus	$168 \times 10^3 \text{ MPa}$
Poisson's Ratio	0.22
Thermal Expansion Coefficient	$3.5 \times 10^{-6}/^\circ\text{C}$
Thermal Conductivity	$150 \times 10^6 \text{ pW}/\mu\text{m } ^\circ\text{C}$
Resistivity	$2.3 \times 10^{-11} \Omega\text{-}\mu\text{m}$

Similar procedure is carried out to obtain the temperature distribution for the modified designs at input voltage of 5V by varying the flexure length. Fig. 5 shows the simulation result and Fig. 6 shows the temperature distribution along the bottom layer for various configurations of thermal actuators.

Fig. 7 delineates the plots of maximum temperature as a function of input voltage. It can be seen from the plots that there is no significant increase in temperature with decrease in the flexure length of the top layer. Fig. 8 delineates the plots of maximum displacement as a function of input voltage for various flexure lengths. It can be seen from the plot that the actuator with a flexure length of 20 μm has a maximum displacement of 10.88 μm at an input voltage of 7 V which is 4.7 μm greater than the one with a flexure length of 50 μm [4]. Short flexure length minimizes the torsion force on the flexural arms, which in turn maximizes the vertical displacement of the thermal actuator.

Figure 5 Ansys simulation result.

Figure 6 Temperature distributions along the bottom layer of actuators with flexure lengths of 20 μm , 30 μm , 40 μm , and 50 μm .

Figure 7 Plots of maximum temperature as a function of input voltage.

Figure 8 Plots of maximum displacement as a function of input voltage.

5. EXPERIMENTAL RESULTS

Various configurations of vertical thermal actuator were fabricated using the PolyMUMPS foundry process. The device dimensions are given in Table 2. The PolyMUMPS chips were released using our in-house HF release and drying process. The scanning electron micrograph (SEM) images of the various configurations are shown in Fig. 9. The

maximum tip deflection of the actuator was determined experimentally using an optical profiler and a reflective microscope. The experimental setup using the optical profiler, *VEECO WYKO NT1100* is shown in Fig. 10. The actuation bias was provided using a current amplifier to the contact pads of actuators by probes. The actuator was dynamically analyzed using the *DMEMS* option available in the optical profiler.

Table 2. Dimensions of the thermal actuator.

Device Dimension	Value
Length of the long arm of the top layer	180 μm
Length of poly1-poly2 via	18 μm
Flexure length of the top layer	20, 30, 40 and 50 μm
Width of the top layer	15 μm
Length of the long arm of the bottom layer	217 μm
Flexure length of the bottom layer	50 μm
Width of the bottom layer	18 μm

Figure 9 Scanning electron micrograph images of the vertical thermal actuators with flexure lengths of (a) 20 μm , (b) 30 μm , (c) 40 μm , and (d) 50 μm .

For the measurement, square waves with amplitudes of 7 V with a 20% duty cycle were supplied. The optical reading was taken at every 10° phase difference. The maximum displacement as a function of phase angle is plotted in Fig. 11.

Figure 10 Experimental setup to measure deflection of actuator using an optical profiler.

(a)

(b)

(c)

(d)

Figure 11 Maximum displacements as a function of phase angle for actuators with flexure lengths of (a) 20 μm , (b) 30 μm , (c) 40 μm , and (d) 50 μm .

It can be seen from the Fig 11 that the thermal actuator with 20- μm long flexures has an average displacement of 11.5 μm at an input voltage of 7 V which is 5.3 μm (85%) greater than the one with a flexure length of 50 μm [4]. Similarly,

the thermal actuator with 50- μm long flexures has an average displacement of 7.5 μm at an input voltage of 7 V. Hence, there is a good agreement between the measured actuator displacement and the finite element analysis.

Figure 12 Initial position of the thermal actuator with flexure lengths of 20 μm seen from a 45°-mirror.

Figure 13 Final position of the thermal actuator with flexure lengths of 20 μm seen from a 45°-mirror at an input voltage of 7V.

The maximum displacement of the thermal actuator can also be obtained using a 45°-mirror under a microscope reflecting the displacement image from the side view. This is to address the concern that the optical profiler uses infrared signals to capture displacement and the heated polysilicon structures may interfere with the optical images. In this method, a CCD camera is focused on the mirror to capture the picture of the actuator deflection. The total deflection is obtained by counting the pixels between the initial and final positions of the actuator. The deflection can also be calculated using simple trigonometric relation, following the method similar to the one in [5]. The initial and final positions of the thermal actuator with flexure length of 20 μm are shown in Fig 12 and 13, respectively. The maximum displacement using this measurement method is 11.32 μm at an input voltage of 7V. Both measurement approaches verified the finite element simulation results.

6. CONCLUSIONS

In this paper, a bidirectional vertical displacement thermal actuator was presented. The device was fabricated using multilayer polysilicon process, PolyMUMPS. The actuator was characterized using an optical profiler. The actuator was modified to achieve higher displacement without significant increase in the body temperature. The theoretical and experimental results were verified using finite element analysis. The actuator can be utilized to design flow sensors, variable capacitors, resistive sensors, optical switches and RF switches.

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