Characterization of Symmetrical and Asymmetrical Polysilicon Surface Micromachined Electrothermal Actuators

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Abstract

Several electrically-driven microactuators have been investigated for positioning individual elements in microelectromechanical systems (MEMS). The most common modes of actuation are electrostatic, magnetostatic, piezoelectric and thermal expansion. Unfortunately, the forces produced by electrostatic and magnetostatic actuators tend to be small, and to achieve large displacements, it is necessary to either apply a large voltage or operate the devices in a resonant mode. On the other hand, piezoelectric and thermal expansion actuators can be configured to produce large forces and large displacements. However, piezoelectric materials are not routinely supported in the fabrication processes offered by commercial MEMS foundries. These limitations have focused attention on thermally-actuated devices for generating the large forces and displacements frequently required to position and assemble complex MEMS. This investigation reports a new polysilicon electrothermal actuator design. In the traditional electrothermal actuator design, the single-hot arm is narrower than the cold arm, and thus, the electrical resistance of the hot arm is greater. When electrical current passes through the device (both the hot and cold arms), the hot arm is heated to a higher temperature than the cold arm. This temperature differential causes the hot arm to expand along its length, thus forcing the tip of the device to rotate about the flexure. The new double-hot arm thermal actuator design eliminates the parasitic electrical resistance of the cold arm by incorporating an additional hot arm. The second hot arm results in an improvement in electromechanical efficiency by providing a return current conductor that is also mechanically-active. Furthermore, in the new electrothermal actuator design, the rotating cold arm can have a narrower flexure compared to the flexure in the traditional device because it no longer needs to conduct an electrical current. The thinner flexure results in an improvement in mechanical efficiency. This research compares the performance of the single- and double-hot arm electrothermal actuator designs. Force and

deflection measurements of both actuator designs as a function of arm length and applied electrical power are presented. The electrothermal actuator designs were accomplished with the MEMSPro® software program, and they were fabricated using the MEMSCAP Integrated Microsystems Multi-User Microelectromechanical Systems (MEMS) Process® (MUMPs) foundry at the Microelectronics Center of North Carolina (MCNC).

Introduction

Numerous electrically-driven microactuators have been investigated for positioning individual elements in microelectromechanical systems (MEMS). The most common modes of actuation are electrostatic, magnetostatic, piezoelectric and thermal expansion [1]. Unfortunately, the forces produced by electrostatic and magnetostatic actuators tend to be small, and to achieve large displacements, it is necessary to either apply a large voltage or operate the devices in a resonant mode. On the other hand, piezoelectric and thermal expansion actuators can be configured to produce large forces and large displacements. Unfortunately, piezoelectric materials are not routinely supported in the fabrication processes offered by commercial MEMS foundries. As a result, these limitations have focused attention on thermally-actuated devices for generating the large forces and displacements frequently required to position and assemble complex MEMS [2].

This research focuses on improving the design and performance of the MEMS electrothermal microactuator [3]. As depicted in Figure 1, a conventional MEMS polysilicon electrothermal microactuator uses resistive (Joule) heating to generate thermal expansion and movement [3]. When current is passed through the actuator, the larger current density in the narrower "hot" arm causes it to heat and expand in length more than the "cold" arm. Since both arms are joined at their free (released) ends, the difference in length of the two arms causes the microactuator tip to move in an arc-like pattern about the flexure element incorporated at the anchor end of the "cold" arm. Removing the current from the device allows it to return to its equilibrium state.

The design of the flexure used in electrothermal microactuators is an important functional element [4]. Ideally, the flexure element should be as narrow as possible. Narrower flexures allow more of the force generated by the thermal expansion of the "hot" arm to cause movement at the tip of the microactuator. In the conventional electrothermal microactuator depicted in Figure 1, electrical current passes through the flexure. If the flexure were to be narrower than the "hot" arm, the temperature of the flexure element would be greater than the "hot" arm, and it could be destroyed by excessive heat. Additionally, the flexure element needs to be sufficiently long so that it can be elastically deflected by the thermally induced length expansion of the "hot" arm. However, if the flexure is too long, movement of the microactuator's tip will be significantly reduced. That is, long flexures will also expand in length when electrical current is applied, thus countering the intended rotational movement. The flexure and "cold" arm contribute to the microactuator's over-all electrical resistance because they complete the electrical circuit for current passing through the "hot" arm. Furthermore, the power dissipated in the flexure and "cold" arm does not contribute to the desired movement of the actuator. Only the power dissipated in the "hot" arm directly translates into the intended movement of the actuator.

The new electrothermal microactuator design depicted in Figure 2 eliminates the parasitic electrical resistance of the "cold" arm by incorporating an additional "hot" arm. The second "hot" arm improves electrical efficiency by providing an active return current path. Additionally, the rotating "cold" arm can now have a narrower flexure element compared to the flexure in a conventional device (Figure 1) because it no longer needs to conduct an electrical current [4].

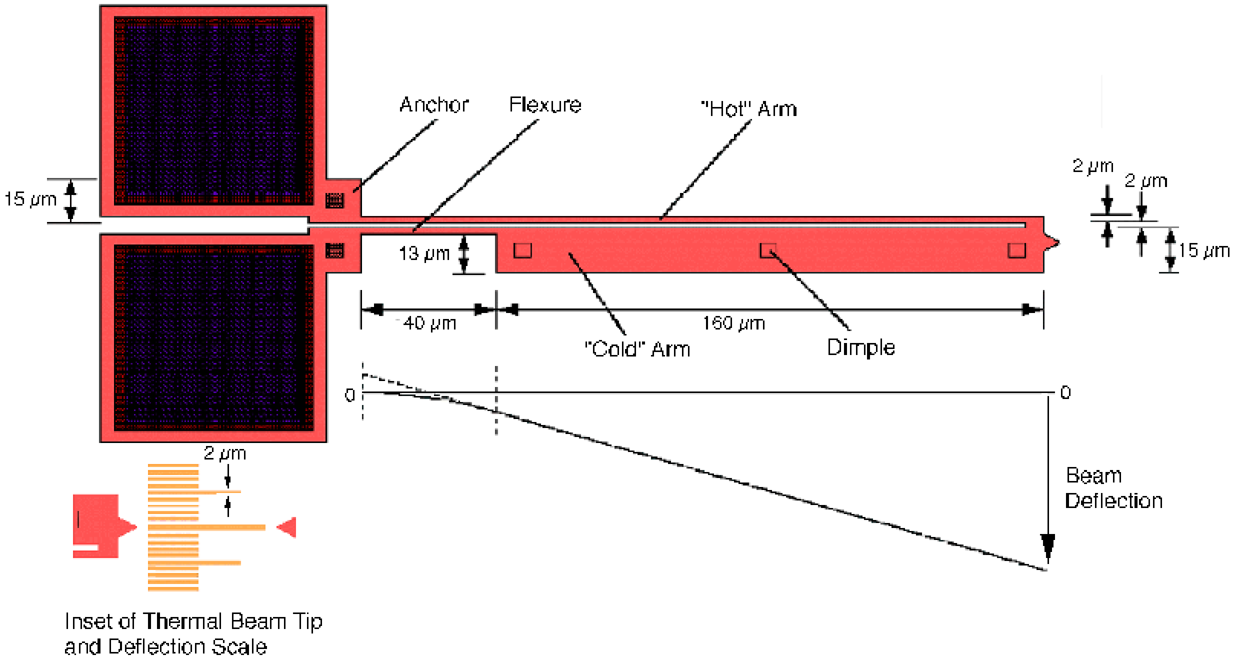


Figure 1. Conventional single–"hot" arm polysilicon electrothermal actuator design with an adjacent simple cantilever beam used to measure deflection force. The 2.0 μm thick polysilicon thermally-deflectable beam is suspended above a silicon nitride dielectric layer via the sacrificial glass etch process. The three dimples (square-shaped features) positioned along the length of the wide segment of the beam act as near-frictionless bearings. The inset depicts a magnified view of the actuator's tip ("pointer" feature) and scale used to measure deflection.

Electrothermal Microactuator Design and Fabrication

The design of the two electrothermal microactuator designs was accomplished with the MEMSPro® CAD program [5], and the devices were fabricated using the MUMPs foundry service [6]. The thermal arms were fabricated from the 2 μm thick, stress-free, electrically conductive, poly 1 releasable layer (Figures 1 and 2). Table I summarizes the dimensions of the electrothermal microactuators investigated.

Adjacent to the pair of mechanical anchors for the "hot" and "cold" arms in the single–"hot" arm microactuator, and the two "hot" arms in the double–"hot" arm device, are a set of adjoining electrical contact pads composed of stacked layers of polysilicon and gold. The actuator's tip deflection scale and the equilibrium rest position triangular index marker (Figures 1 and 2) were rendered using the poly 0 layer. To minimize stiction problems, the MCNC MUMPs carbon dioxide (CO_2) critical-point drying scheme was utilized [6].

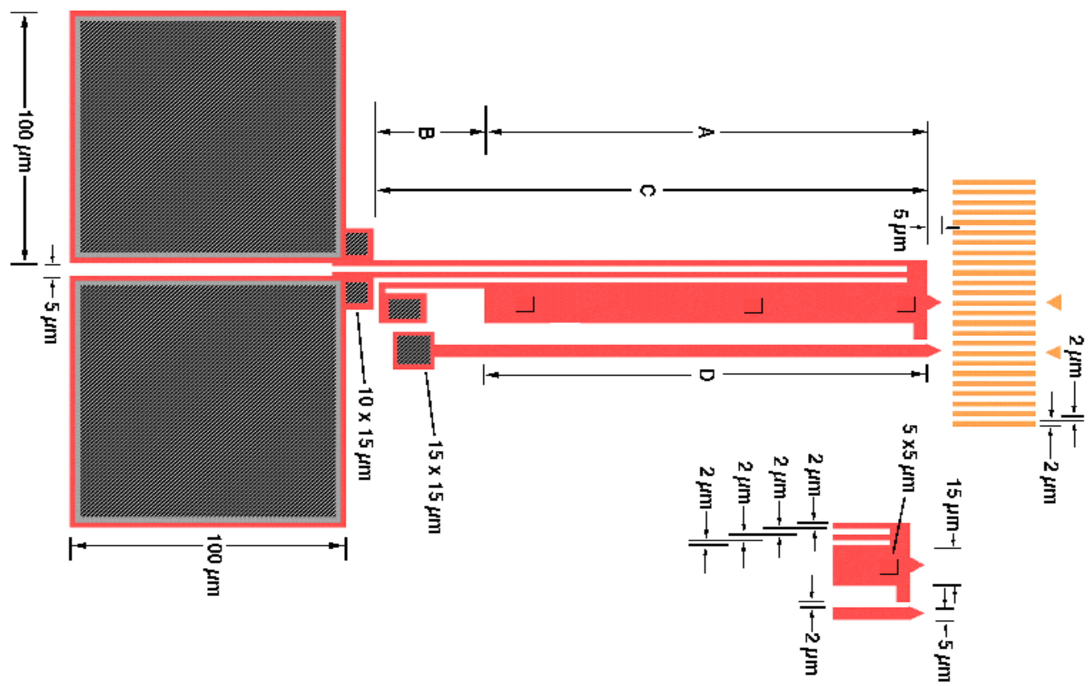


Figure 2. Improved double–"hot" arm polysilicon electrothermal microactuator design with an adjacent simple cantilever beam used to measure deflection force. The 2.0 μm thick polysilicon thermally-deflectable beam is suspended above a silicon nitride dielectric layer via the sacrificial glass etch process. The three dimples (square-shaped features) positioned along the length of the wide segment of the beam act as near-frictionless bearings. The inset depicts a magnified view of the actuator's tip ("pointer" feature) and scale used to measure deflection.

Table I. Design Dimensions of the Critical Components in the Single– and Double– "Hot" Arm Electrothermal Microactuators. (All dimensions in μm).

Component	Single–"Hot" Arm	Double–"Hot" Arm
"Cold" Arm Length	100, 120, 140, 160, 180, 200	100, 120, 140, 160, 180, 200
"Cold" Arm Width	15	15
Flexure Width	2	1.5
"Hot" Arm Length	150, 170, 190, 210, 230, 250	150, 170, 190, 210, 230, 250
"Hot" Arm Width	2	2.5
"Hot" and "Cold" Arm Separation	2	2
"Hot" Arm Separation	not applicable	2

To experimentally measure the force generated at the tip of an activated electrothermal microactuator, a long and narrow simple cantilever beam was positioned parallel to the "cold" arm in each design (Figures 1 and 2). The end of these 5 μm wide simple cantilever beams closest the electrical contact pads was anchored to the silicon nitride substrate. Two dimple structures (each 1 μm square) were uniformly spaced along the simple cantilever beams to minimize frictional losses should they contact the silicon nitride substrate during in-plane translation. The deflection marker positioned at the other end of the simple cantilever beam was incorporated along with a poly 0 deflection scale to measure the simple cantilever beam's in-plane translation when contacted by an activated electrothermal microactuator. The physical gap between the deflectable tips of the simple cantilever beam and the "cold" arm of the electrothermal microactuator was 2 μm.

Experimental Results

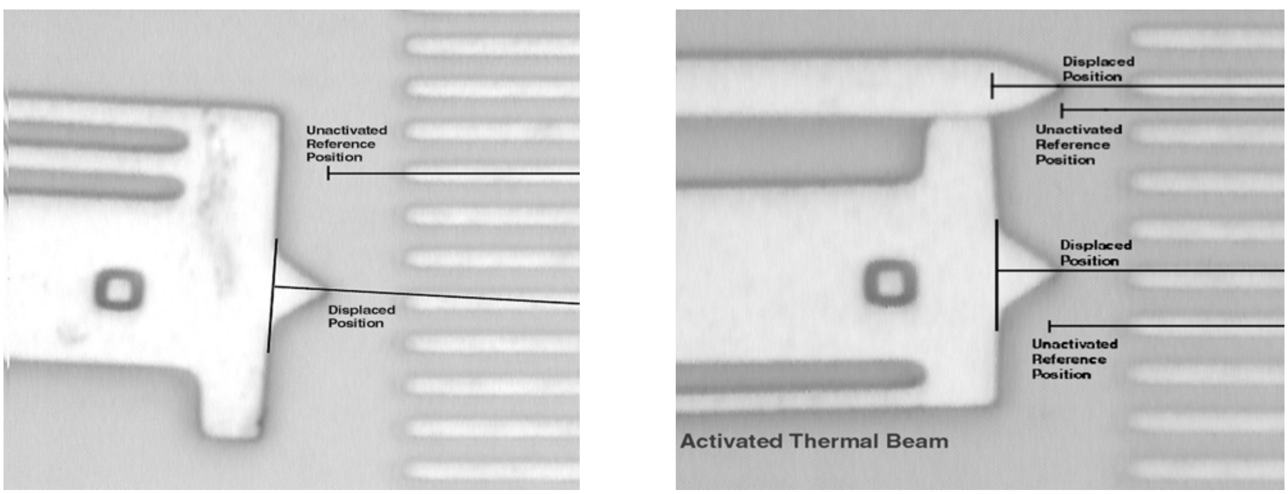
The tip deflection characteristics of the two electrothermal microactuator design variants were experimentally measured using a Karl Suss microprobe station (model PM 5; 2000x magnification), a pair of Karl Suss RF microprobes (model PH 150), and a Keithley electrometer/programmable DC power supply (model 617). To implement these measurements, the simple cantilever beam (Figures 1 and 2) used to accomplish the tip force measurement was carefully removed with a microprobe. The tip deflection magnitudes for the set of single–"hot" arm and double–"hot" arm electrothermal microactuators described in Table I were measured as a function of the externally applied DC voltage and current. While accomplishing these measurements, it was observed that when the "cold" arm length (Table I) was greater than or equal to 200 μm, the motion of the microactuator was very irregular and erratic; otherwise the motion of the shorter devices was very smooth and highly reproducible. A subsequent high-magnification microscopy investigation revealed that when the "cold" arm length was greater than or equal to 200 μm, the released end of the actuator was likely being deflected by residual stress gradients, and it made physical contact with the substrate. Figure 3(a) depicts the method adopted to measure a 11.1 μm tip deflection event observed with a double–"hot" arm electrothermal microactuator whose "cold" arm length was 150 μm. The plot illustrated in Figure 4 captures the measured tip deflection characteristics of the single–"hot" arm and double–"hot" arm electrothermal microactuators for "cold" arm lengths (Table I) equal to 150 μm versus the activation electrical power (activation voltage x activation current). Several authors have modeled the deflection characteristics of the electrothermal microactuator and report that the activation power (W) can be related to tip displacement (d) by an m^{th}-power relationship (that is, $d = k \times W^m$, where k is a constant of proportionality) [1-4]. The smooth curves depicted in Figure 4 represent the Levenburg-Marquardt non-linear least-squares curve fit results for the two electrothermal microactuator designs, and the two plot symbols represent the experimentally measured data. For both electrothermal microactuator designs, the 150 μm "cold" arm length manifested the largest tip deflection magnitude.

Figures 1 and 2 depict the geometry and position of an adjacent simple cantilever beam that was used to measure the force imparted on it by the tip of an activated electrothermal microactuator. Cochin and Cadwallender [7] have modeled the incremental side-to-side deflection (d) of a simple cantilever beam due to the application of an in-plane force applied to its tip (F_{tip}) as:

$$F_{tip} = \frac{E\,h}{4}\left(\frac{b}{l}\right)^{3} d$$

where losses due to friction have been ignored, and

E = Young's modulus of elasticity (average value of160 GPa for the MEMSCAP/MUMPs polysilicon [6])
h = the beam's width (Figures 1 and 2; 10 μm)
b = the beam's thickness (Figures 1 and 2; 2 μm for poly 1)
l = the beam's suspended length (Table I, 290.5 μm).



(a) **(b)**

Figure 3. Optical microscope (2000x magnification) showing the tip deflection behavior of the electrothermal microactuaors whose "cold" arm length is 150 μm. (a) 11.1 μm tip deflection (24.3 mW applied electrical power) for the double–"hot" arm design. (b) Deflection of the simple cantilever beam caused by an 8.1 μN microactuator tip force generated by the single–"hot" arm device.

Figure 4. Plot of tip deflection (d) versus activation electrical power (mW) for the single–"hot" arm and double–"hot" arm electrothermal microactuator design variants whose "cold" arm lengths are 150 μm. The plot symbols depict the averaged experimentally measured result for five different electrothermal actuators. The smooth curve corresponds to the Levenburg-Marquardt nonlinear least-squares curve fit for an equation of the form:

$$d\ (\mu m) = k(\mu m/mW) \times [\ W\ (mW)^{m}$$

(k = 0.005; m = 2.344 for the single–"hot" arm actuator and k = 0.028; m = 1.875 for for the double–"hot arm actuator).

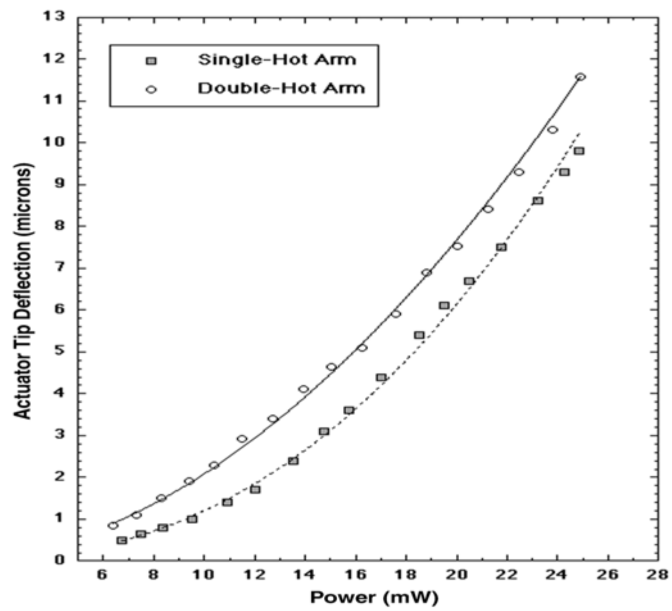


Table II. Tip Deflection Force Delivered by the Single– and Double– "Hot" Arm Electrothermal Microactuators* to an Adjacent Simple Cantilever Beam.

"Hot" Arm Length (μm).	Single–"Hot" Arm Electrothermal Actuator Tip Force (μN)	Double–"Hot" Arm Electrothermal Actuator Tip Force (μN)
150	1.2	4.3
170	2.2	6.4
190	2.3	6.5
210	1.8	4.8
230	4.1	Not Measured
250	Not Measured	Not Measured

* Not measured due to friction

For each of the single–"hot" arm and double–"hot" arm electrothermal microactuator design variants, five devices for each of the six different "cold" arm lengths were experimentally characterized to establish tip generated force. It was observed that when the "cold" arm length (Table I) was greater than or equal to 200 μm, the motion of the two microactuator designs was irregular and erratic; otherwise the motion of the shorter devices was smooth and highly reproducible.

The microprobe station was used to measure the tip deflection of the simple cantilever beam, and the Keithley electrometer/programmable DC power supply was used to apply the activation power. Figure 3(b) depicts the method adopted to measure the simple cantilever tip deflection event observed with a single–"hot" arm electrothermal microactuator whose "cold" arm length was 150 μm. Table II summarizes the tip force generated by the electrothermal microactuators.

Summary and Conclusions

Single– and double–"hot" arm electrothermal microactuators capable of producing in-plane tip deflections spanning 1–10 μm and generating tip forces exceeding 8 μN were designed and fabricated using the three-level polysilicon surface-micromachined foundry service that is available as the Multi-User Microelectromechanical Systems (MEMS) ProcesS (MUMPS) through MEMSCAP, Inc. Microactuator tip deflections for both design variants were experimentally measured for those devices whose "cold" arm length was 150 μm or less. The quantitative tip deflection (d) data was least-squares curve fitted to an established relationship of the form, $d = k \times W^{m}$, where W is the applied electrical power and k and m are constants. For a given excitation power level, the double–"hot" arm electrothermal actuator produced an average 14 percent more tip deflection than the single–"hot" arm device. When the "cold" arm length in each of the two microactuator design variants was greater than or equal to 200 μm, movement of the devices were observed to be very erratic and irreproducible. This behavior occurred because residual stress gradients deflected these longer microactuators toward the underlying substrate, resulting in significant friction with respect to in-plane motion. The double–"hot" arm electrothermal microactuator with a 150 μm "cold" arm length generated approximately 16 percent more tip force compared to the single–"hot" arm device. Both electrothermal microactuator design variants with a "cold" arm length of 150 μm produced greater tip deflection magnitudes and generated greater tip forces compared to those devices with "cold" arm lengths of 150 μm and 200 μm.

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Biographies

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