Design of Vertical-Lateral Thermal Actuators for MEMS

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ABSTRACT

This paper focuses on the design of compact thermal actuators capable of both lateral and vertical actuation. Several different approaches to vertical and lateral actuation were combined to design a device capable of both vertical and lateral deflection. This paper presents suggested test structures and experiments and expected results for such a device.

Keywords

Thermal actuator, MEMS, MUMPs, heatuator

1. INTRODUCTION

Thermal actuators have proven to be very useful in MEMS applications, especially in actuating optical MEMS mirrors [7] and automated assembly [6], which require large forces and displacements. Thermal actuators are more power efficient than electrostatic actuators. Although there has been some exploration of vertical thermal actuators and extensive exploration of lateral thermal actuators, there has been no exploration of thermal actuators that are capable of both lateral and vertical movement.

The most extensive research of lateral thermal actuators has been done with variations on the heatuator. The traditional heatuator (pictured in figure 1.a.) involves the resistive heating of two beams of different widths and therefore electrical resistance [8]. The narrow or hot arm heats up and expands more than the wide or cold arm deflecting the device toward the cold arm. Another variation of this series current connected heatuator uses two hot arms and one cold arm [3]. The double hot arm heatuator (pictured in figure 1.b.) runs the current through only the hot arms thus eliminating the parasitic electrical resistance cold arm. This design was found to be more power efficient and capable of larger force and deflection per area. The traditional heatuator can also be wired in parallel (pictured in figure 1.c.) [5]. When current is split between the narrow and wide arms, the wide arm with lower resistance carries more current. The wide arm then becomes the hot arm and expands more deflecting the device towards the narrow arm.

Much less work has been done in the exploration of vertical thermal actuators. One method of vertical actuation is very similar to the lateral heatuator only the wide and narrow arms lay on different layers of poly so that the resulting deflection is in the vertical direction [4]. Another approach to vertical thermal actuators called thermal bimorph expansion consists of stacking layers of materials with differing thermal expansion coefficients [2]. When resistively heated, the layer with the higher thermal expansion coefficient expands most actuation the device vertically in the direction of the layer with the lower thermal expansion coefficient.

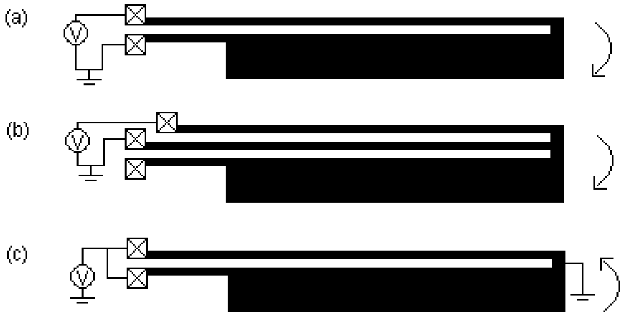

Figure 1. (a) Series arrangement of basic heatuator (b) Double hot arm heatuator (c) Parallel arrangement

This paper explores the possibility of using a combination of the vertical and lateral thermal actuation methods described above to design a compact thermal actuator capable of both vertical and lateral deflection. Section 2 describes the fabrication process and methods used to design the vertical-lateral thermal actuator structures. Section 3 describes suggested test structure variation and methods of collecting experimental data. Section 4 presents expected experimental results and section 5 presents conclusions.

2. DESIGN

2.1 Fabrication Process (MUMPs)

All devices discussed in this paper were designed for fabrication in the Multi-User MEMS Processes (MUMPs) described most clearly in the double hot arm heatuator paper [3]. MUMPs offers three layers of polysilicon and two sacrificial layers of phosphosilicate glass on a bare layer of silicon nitride. The last two polysilicon layers are releasable. Gold is evaporated onto the device at the end of the process by low-pressure chemical vapor deposition. Table 1 identifies the order and thickness for each film deposited in MUMPs. Depressions of 0.75 um can be made on the first sacrificial layer adding dimples under long structures to keep the structure from sticking to the substrate when drying after the release. The polysilicon layers and the substrate are highly doped with phosphorous to decrease electrical resistance. After construction, the sacrificial layers are removed in a bath of buffered hydrofluoric acid.

Table 1. Layers used in MUMPs [3].

Layer Name	Thickness
Nitride (silicon nitride)	0.6
Poly-0 (bottom polysilicon layer)	0.5
1st Oxide (phosphosilicate glass)	2.0
Poly-1 (middle polysilicon layer)	2.0
2nd Oxide (phosphosilicate glass)	0.75
Poly-2 (top polysilicon layer)	1.5
Metal (gold)	0.5

2.2 Design Methods

There has been experimentation with adding the MUMPs gold layer to the cold arm in lateral heatuators in order to lower its resistance. This is a very good idea since gold has a much lower resistance than polysilicon. The problem with this approach is that the cold arm acts like a bimorph curling the beam out of the plane and making it harder to deflect [8]. The way of using MUMPs for vertical actuation without using the gold layer is to fabricate the two beams in different layers on top of one another and make one wider than the other [4]. If a series current is run through the two layers, the higher resistance of the narrower beam will cause it to expand and deflect the actuator toward the wide beam. Figure 2 shows how MUMPs can be used to make a vertical actuator. A dimple is placed at the end of the structure to avoid sticking during fabrication.

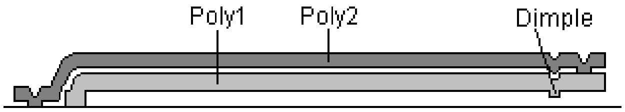

Figure 2. Use of MUMPs in vertical thermal actuation

In order to enable the vertical actuator with lateral actuation, each layer should be designed to resemble a heatuator. As shown in the double hot arm method for lateral heatuators, current need not run through every arm of the actuator [3]. In fact, directing current away from the cold arm eliminates its parasitic electrical resistance, thus improving the efficiency and the deflective performance of the actuator. As long as no current is running through the cold arm, its width has no bearing on the electrical performance of the actuator, only on the actuator mass. Therefore, the cold arm and hot arm could have the same width, and either arm could serve as the cold or hot arm depending on where the current flows. An actuator needs only three arms in order for this process to work but if two sets of beams are layered on top of one another using poly1 and poly2 from MUMPs, there are four arms. Figure 3 shows a vertical-lateral actuator design with all arms of equal width, ideal for double hot arm actuation and maximizing the directions of deflection.

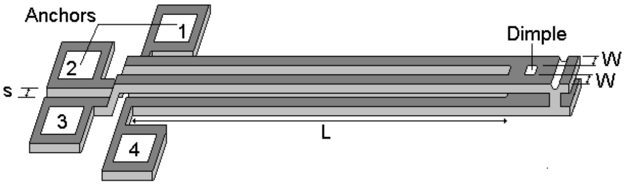

Figure 3. Basic design of a vertical-lateral actuator

There is no need for a wide and narrow arm as in the single layer heatuator method. In fact, it is better that both layers have as similar properties as possible eliminating the effects of differential resistive heating. The poly1 and poly2 layers differ in thickness by 0.5 um due to the MUMPs process but the effects should be quite minimal compared to the effects caused by the optimal 7:1 arm width ratio of the basic heatuator [8].

Assuming all four legs have very similar electrical properties, if voltage is paced between anchors 1 and 2 or 3 and 4 only, the actuator deflects laterally toward the acting cold arms. If voltage is placed between 1 and 4 or 2 and 3 only, the actuator deflects vertically toward acting cold arms. If a combination of lateral and vertical voltage is applied, the actuator should respond with respective combined lateral and vertical actuation. However, if combined voltage is applied, one arm will be affected by the combination of two currents, the sum of which is limited by the same maximum current as if only one voltage is applied. Therefore, any combined actuation will be less than if the maximum current were used for only lateral or vertical actuation.

3. TEST STRUCTURES

Arrays of test structures should be fabricated in order to test the actuating properties of this new device. Test should include measurement of lateral and vertical deflection vs. current and force applied under load vs. current.

The following parameters from figure 3 are suggested for the vertical-lateral actuator. W = s = 2 um. Experiments have shown that the power needs are boosted significantly when the hot arm width exceed its thickness [8]. Thus the arm width is made equal to its thickness. This also allows for just as easy vertical deflection as lateral deflection. The separation s is made as minimal as possible to maximize deflection. L should be varied in arrays to characterize the effects of change in length on this new double layer design. Let L vary between 100 and 300 um.

3.1 Lateral Measurements

Figure 4 shows the basic design of a test structure that measures lateral deflection [8]. A pointer is placed at the end of the actuator in poly1. A scale in poly1 is anchored in front of the pointer with 2 um width teeth placed 2um apart. The current should be slowly increased and then recorded when the pointer lines up with the next scale tooth. The maximum repeatable deflection before the polysilicon arm starts to melt is the maximum deflection. The longer the pointer the greater the resolution of the measurement will be. However, the pointer should not be too long as not to disrupt the performance of the actuator.

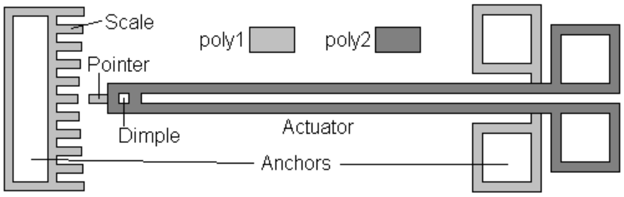

Figure 4. Lateral deflection test structure

Figure 5 shows the basic design of a test structure that measures lateral force under load [1]. A beam is tethered in the direction of deflection from the actuator to a beam and pointer. A scale much like the one used in the deflection measurement test structure is used to measure the deflection of the beam. The force applied by the actuator can be calculated by the beam deflection. The force is given by equation (1).

$$F = \left[\frac{Etw^3}{2(3a^2L - a^3)}\right] \times d \qquad (1)$$

E is the effective Young's modulus, which is 162 GPa for polysilicon. The beam thickness is t = 2 um in MUMPs poly1. The distance from the base of the beam to the point of applied force is a. The deflection of the beam is b. The width and length of the beam are w and L respectively.

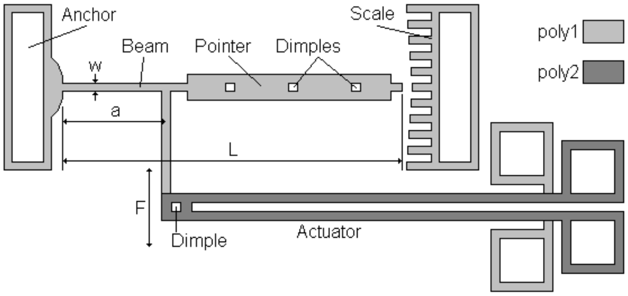

Figure 5. Lateral force tester

3.2 Vertical Measurements

There is very little that can be done in the way of test structures to measure the vertical deflection and force under load. A Microscope-based laser interferometer can be used to measure vertical deflection and a weight-balanced force tester can be sued to measure vertical force under load [2].

4. EXPECTED RESULTS

Expected results are idealistic and are performed to get a best-case scenario result.

4.1 Deflection vs. Current

Expected deflection of the actuator in either the vertical or lateral direction with respect to current can be calculated with the electrical and thermal characteristics of the polysilicon and physical dimensions of the actuator. Deflection of the actuator is a function of the radius of curvature of the device. Assuming that the beams are of length L with radius of curvature r, the deflection d can be obtained geometrically from r and L as long as L >> r [2]. The deflection is given by $d = L^2 / 2r$. The radius of curvature of two beams bending as one can be calculated by the distance between the centers of the two beams b, original beam length L, and the difference in length between the two beams δ. The radius r is given by $r = L\, b / \delta$. The change in length δ is a function of the change in temperature T and is given by $\delta = L\, \alpha\, T$ where α is the coefficient of thermal expansion of polysilicon. The change in temperature T is given by $T = I^2 R / L\, \kappa$ where I is the current applied, R is the electrical resistance of the beams, and κ is the thermal conductivity of polysilicon. The electrical resistance R is given by $R = \rho\, 2L / w\, t$ where L is the original length of one of the two expanding beams, w and t are the width and thickness of the beams respectively, and ρ is the resistivity of polysilicon.

All of these equations are then combined to express actuator deflection with respect to current. This deflection is given by equation (2).

$$d = \frac{\alpha\rho}{\kappa}\frac{L^2}{w\,t\,b} I^2 \qquad (2)$$

The thickness of the beams are identical in vertical actuation with t = 2um for actuation away from the substrate and t = 1.5 um for actuation toward the substrate. The thicknesses of the two thermally excited beams are different in lateral actuation because they are in different poly layers. The equation for lateral deflection using two different beam thicknesses is given by equation (3) where t_1 = 2 um and t_2 = 1.5 um.

$$d = \frac{\alpha\rho}{\kappa}\frac{L^2}{wb}\frac{1}{2}\left[\frac{1}{t1}+\frac{1}{t2}\right] I^2 \qquad (3)$$

The distance between centers of the two beams b is dependant on the thickness of the beams for vertical deflection and the widths of the beams for lateral deflection. For vertical deflection b = 0.5t1 + 0.5t2 + 0.75 = 2.5 um. For lateral deflection b = 0.5w + 0.5w + s = 4 um.

The coefficient of thermal expansion α used is 2.5E-6 1/K. The electrical resistance ρ used is 0.2 Ωm. The thermal conductivity κ used is 100 W/mK. The original length of the beams L will vary from 100 to 300 um in 50 um increments. The resulting deflection vs. current plot is quadratic. Figure 6 displays the expected plot of actuator vertical deflection away from the substrate vs. current for several varying lengths. Figure 7 displays the expected plot of deflection vs. current for an actuator of length 200 um in the lateral direction, vertical direction away from the substrate, and vertical direction toward the substrate.

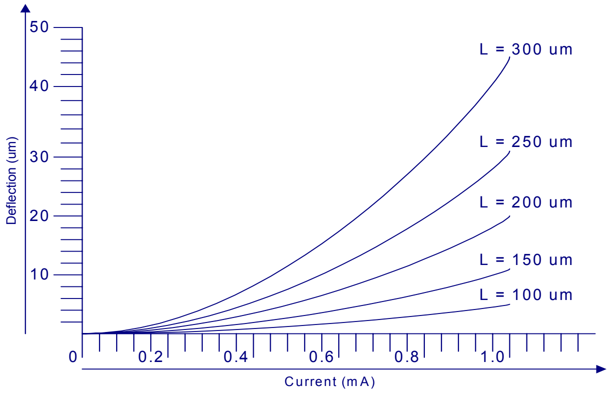

Figure 6. Deflection vs. Current for various lengths

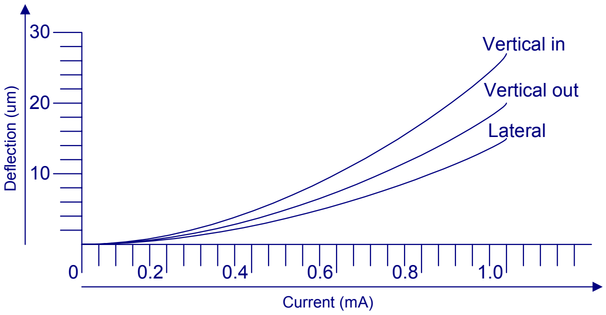

Figure 7. Deflection vs. Current for various directions

Because of the two layer design and the absence of the extra mass of a wide arm, the actuator should be able to be lengthened much more than the single layer lateral heatuators. When voltage is applied to get only lateral deflection, some downward vertical deflection may occur due to the different thicknesses of the two poly layers. This deflection is expected to be very minimal, especially as the actuator is shortened.

4.2 Force vs. Current

Expected force delivered vs. current is dependant on the change in length of the beams δ and the Young's modulus of polysilicon E. This is the force generated from the expansion of the beams and does not take into account the force lost in bending the actuator itself. In fact the force lost increases as the deflection increases. This lost force is expected to be very small compared to the force generated; therefore it is neglected in this calculation. The force F is given by equation $F = 2\,\delta\, w\, t\, E / L$.

By substituting for δ as before, the force F can be expressed with respect to the applied current. This force is given by equation (4).

$$F = \frac{4\alpha\rho E}{\kappa} I^2 \qquad (4)$$

Notice that the force is not dependant on length, width or thickness of the beams. The force is dependant only on the electrical and thermal characteristics of the polysilicon and the applied current. Therefore, the force vs. current plot should not change as the actuator length is increased, or between different directions as the thickness of the excited beams vary. Figure 8 displays the expected plot of force vs. current.

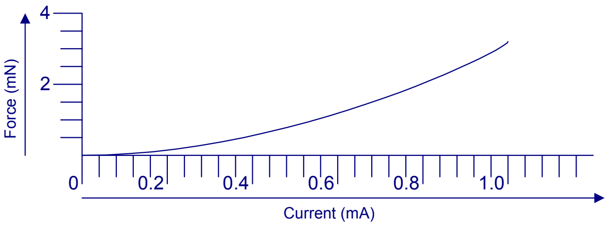

Figure 8. Expected Force vs. Current plot

5. CONCLUTIONS

The vertical-lateral thermal actuator may prove to very useful in designing MEMS devices. Both vertical and lateral thermal actuators have been used to design optical MEMS devises that involve the manipulation of mirrors [7]. They are also often used in automated structure assembly [6]. The vertical actuators are used to lift one end of a plate or mirror off the substrate in order to provide the leverage need for the lateral actuators to push the plate or mirror into position. But separate design and placement is required for these actuators. If the vertical-lateral actuator were placed in arrays as in [9], they would be able to provide both the leverage and lateral force required to assemble a structure or move a mirror.

Once these individual vertical-lateral actuators have been tested and characterized, the applications of arrays of these structures can be researched. Arrays of thermal actuators are created to increase the total force. One vertical-lateral actuator is already like an array of two heatuators stacked on top of one another.

Research has been made on the back bending effects on both vertical and lateral actuators [4] [6] by over heating the hot arm until the poly reflows and the actuator is repositioned in a backward position. Such studies could be extended to the vertical-lateral actuator as well.

6. REFERENCES

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