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# Polysilicon Vertical Actuator Powered with Waste Heat

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***Abstract*-This paper presents a new micro thermal actuator with bi-directional vertical motion. Traditional thermal actuators require an electric current to generate heat by Joule effect and obtain motion via thermal expansion. This work offers a simplified polysilicon thermal actuator designed to operate with an external heat source and, for example, scavenge heat from the surrounding medium. The actuator was fabricated using a standard surface micromachining process (PolyMUMPs). The thermal actuation characteristics, analysis, and experimental results for this novel micro-mechanical device are provided to illustrate performance and potential applications.**

## I. Introduction

Thermal actuation has been extensively used in Micro-Electro-Mechanical Systems (MEMS). Thermal actuators typically exhibit larger displacements and forces than electrostatic actuators and their thermal expansion is linearly related to the applied heat.

Deflection of thermal actuators strongly depends on their geometry. The principle of operation is to make an electric current flow through the device structure and induce Joule heating. The corresponding increase in temperature causes the structural material to expand and generate deflection when the device is mechanically constrained.

As Joule heating consumes considerable electrical energy, typical thermal microactuators also require an external battery that is several times the size of the microsystem itself. It is the power supply unit that severely limits portability and practicability of microsystems technology.

The idea of exploiting energy resources from the environment presents an opportunity to develop autonomous microsystems that do not rely on a bulky battery with fairly limited energy storage capacity. Through the application of energy harvesting techniques, micro-devices could scavenge power from ambient heat, light, vibrations, EM waves, etc.

Microactuator technologies find applications in a great variety of fields where a reduction in size and weight is important. Particularly compelling is the possibility of implementing MEMS and electronic circuitry together on the same substrate that can be manufactured in high volumes and low cost due to the mass production nature of semiconductor wafers.

As an alternative to the classical electrically driven thermal actuator, this work presents the design and characterization of a vertical actuator that operates by exploiting thermal energy already present in the surrounding environment. Such conditions in which a high heat density is available are very common in practical situations where MEMS are usually found, for example in the automotive industry and in every application using electronic circuitry that dissipates heat.

## II. Design Concept

Historically, the analysis of thermal actuators began with the development of the horizontal thermal actuator [1, 2]. The basis for the operation of these devices consists in obtaining asymmetrical thermal expansion between two adjacent and physically joined structural microbeams (the 'hot' and 'cold' arms respectively). Numerous works on the subject of lateral thermal actuators have been previously published [1-4]. The actuation principle of a vertical thermal actuator (VTA) is based on that of a horizontal actuator.

Variations of the vertical actuator are well documented [5-7]. One of the preferred architectures for implementing a vertical thermal actuator is illustrated in Fig. 1. This design comprises two 'U' shape structures, one on top of the other, that are connected at the tip of the actuator. If a voltage is applied between the anchor pads of the top (or bottom) level structure, electrical current will flow solely through this layer thereby increasing its temperature and causing a correspondent thermal expansion that will deflect the tip of the actuator downwards (or upwards).

This paper reports a customized actuator design that generates vertical deflection as a result of external heating of the device. A simplified geometry that does not entail providing a return path to ground for a driving current on the same layer is introduced in Fig. 2.

The structure is formed by two cantilever-type beams fabricated in two different layers one on top of the other and separated by an air gap. The beams are independently anchored on the substrate at one end and linked to each other at the other end by means of a via. The width of the upper cantilever is made smaller than that in the lower level so that the beams are asymmetric. Also, the top layer is about 25% thinner than the bottom one due to characteristics imposed by the MUMPs fabrication process.

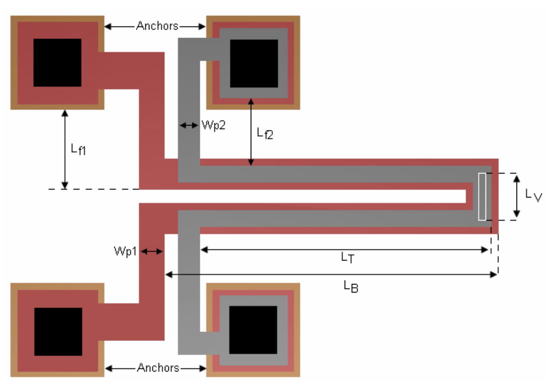


Fig. 1. The classical 'U' shape electrothermal vertical actuator.

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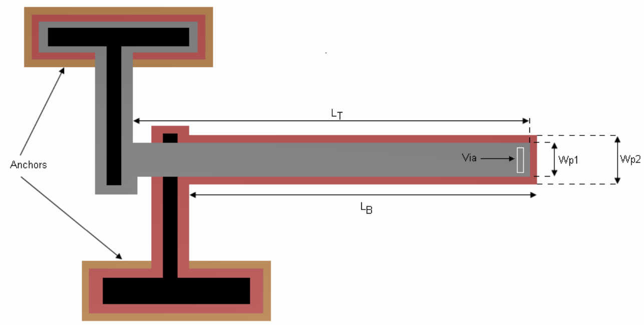


Fig. 2. Schematic view of the proposed double single- beam vertical thermal actuator.

In the presence of a heat source, energy is transferred to the structure of the actuator which in turns increases its temperature. The different geometry of the two microbeams leads to a net expansion of the top layer structure that generates vertical deflection in the direction of the substrate.

Bidirectional displacement may be achieved if heat is applied separately through one of the anchors. In such case, the temperature along the actuator will decrease as one moves in the direction of heat flow as dictated by heat transfer theory. Accordingly, one of the beams will expand more than the other, driving the tip of the actuator against the colder beam.

Among several options that can be applied to more easily drive the actuator independently at either anchor pad is the use of flip-chip transfer technology [8]. Flip-chip techniques allow releasing the actuator from its substrate and liberating the driving pads that may be transferred onto another substrate to integrate a system on a chip.

Design concept relies on the availability of a sufficiently high heat source. External heat sources are fairly common in environments where MEMS find practical use. Examples include automotive and aerospace industry where high heat transfer rates and temperatures beyond 500°C are commonly available [9]. Another potential widespread source of heat for MEMS is found in modern electronic VLSI integrated circuits that may have power densities in excess of 40W/cm$^2$ [10, 11].

## III. Thermal Analysis and Modeling

### A. Temperature Distribution

The thermal analysis of the vertical thermal actuator illustrated in Fig. 2, treats the two microbeams as elements that are connected in series as depicted in schematic of Fig. 3. The total length of the device is $L_T+L_V+L_B$ with the segment $L_B$ being thicker than $L_T$ as indicated before. The following analysis also assumes that heat is applied at the anchor pad of the upper beam while the anchor of the lower beam is kept in contact with the substrate at room temperature.

The heat losses by radiation may be ignored based on the fact that radiation becomes significant only at high temperatures (>1000°C) [12] while operating temperatures for this kind of actuators are relatively low. The steady-state spatial thermal distribution can be derived from examining a differential element of the hot-arm structure of width *w*, thickness *t* and length Δx as illustrated in Fig. 4.

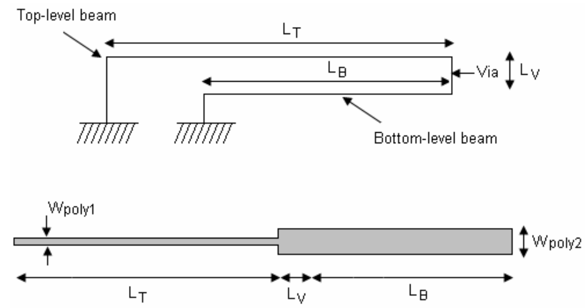


Fig. 3. Simplified coordinate system and diagram of the 'unfolded' actuator of Figure 2 showing the two microbeams connected in series.

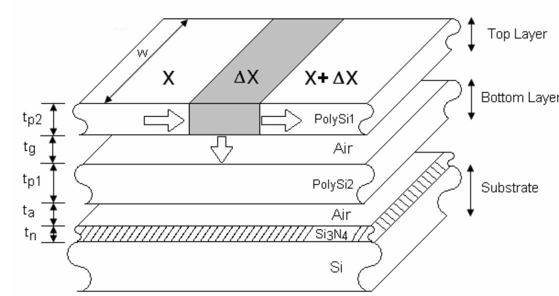


Fig. 4. Cross-sectional view of the actuator's structure.

Following the First Law of Thermodynamics, under steady-state, the energy brought into the element at point x is equal to the energy that comes out at point x+Δx plus the energy which is transferred to the ambient:

$$-kwt\left.\frac{dT}{dx}\right|_{x} = -kwt\left.\frac{dT}{dx}\right|_{x+\Delta x} + hw(T-T_a)\Delta x \qquad (1)$$

where $k$ is the thermal conductivity of the structural material, $T$ is the operating temperature, $T_a$ is the ambient temperature, and $h$ is the convection coefficient that accounts for the heat losses by conduction through the air.

After re-arranging equation (1) and taking the limit as $\Delta x \to 0$, the following second-order differential equation is obtained:

$$\frac{d^2T}{dx^2} - \frac{h}{kt}(T-T_a) = 0 \qquad (2)$$

If changing variables in the form of $\theta = T - T_a$ and $B = \sqrt{\frac{h}{kt}}$, the general solution for equation (2) is:

$$T_{(x)} = T_s + C_1 e^{Bx} + C_2 e^{-Bx} \qquad (3)$$

A particular solution for boundary conditions $\theta_{(0)}=\theta_2$ and $\theta_{(L)}=0$ yields:

$$C_1 = \frac{\theta_2}{1-e^{2BL}}\ ,\ C_2 = \theta_2 - C_1 \qquad (4)$$

Based on equations (3) and (4), Fig. 5 presents an example for the thermal distribution along the beams of the vertical actuator with a total length of 395µm.

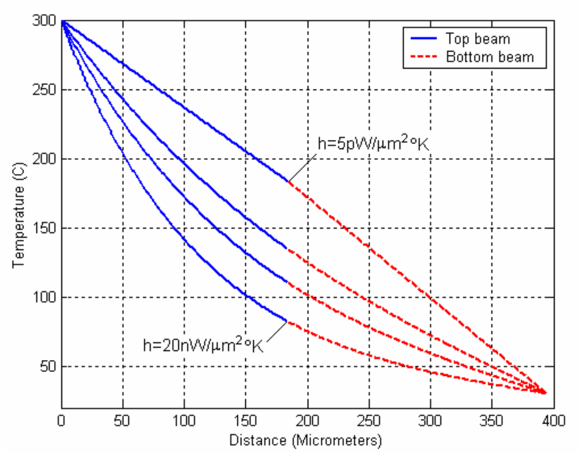


Fig. 5. Solution for temperature distribution along the actuator beams for different values of the convection coefficient h.

Estimation of the heat convection coefficient is a non-trivial task as it can change dramatically from one situation to the next. The effect of the exact value of the convection coefficient h on the temperature profile can be observed as the distribution changes from a linear to exponential shape.

## B. Thermal Expansion

Thermo-mechanical actuation has been comprehensively studied in MEMS [2, 3, 7]. The linear thermal expansion ΔL is given by the following set of equations:

$$\Delta L = K^{-1} F_{thermal}\ ,\ \ F_{thermal} = A\sigma\ ,\ \ \sigma = E\alpha\Delta T \quad (5)$$

where K is the stiffness coefficient, A is the cross-sectional area, E corresponds to the Young's Modulus, $\Delta T=(T-T_a)$, σ represents the thermal stress and α is the thermal expansion coefficient of the material.

The thermal expansion for each of the two arms is obtained by integrating along the beam structure:

$$\Delta L = \alpha \int_0^L (T - T_a) dx \quad (6)$$

and substituting the appropriate temperature distribution from equation (3) yields:

$$\Delta L = \alpha \int_0^L (C_1 e^{Bx} + C_2 e^{-Bx}) dx \quad (7)$$

Finally, the mechanical deflection of the actuator can be estimated based on the thermal expansion by using some of the well established structural engineering methods presented in [3, 7] that analyze the bending moments acting on the hot-arm by solving a set of simultaneous equations.

## C. Finite Element Simulation

To simulate, finite element analysis (FEA) was performed using the commercial software ANSYS™. Multi-physics models including mechanical and thermal domains were used while imposing boundary conditions as mentioned above. In modeling, material properties and characteristic parameters of the selected fabrication process were considered.

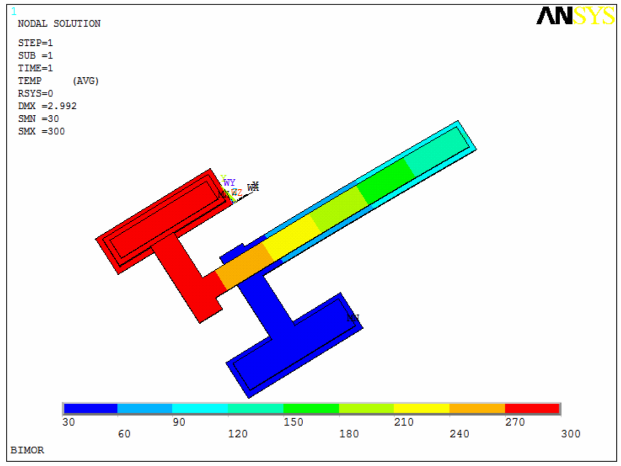


Fig. 6. Numerical results for the temperature distribution of the VTA.

Fig. 6 shows the temperature distribution of the thermal actuator when the anchor pad of the upper level microbeam is brought to 300°C. Simulation results for the out-of-plane tip deflection of the actuator as a function of temperature behave as predicted by the analytic model in [2].

# IV. Fabrication and Experimental Results

The proposed vertical thermal actuator was fabricated using the commercial Multi-User MEMS process (MUMPs), comprising three standard layers of surface micromachined polysilicon. The actuator was then released removing the sacrificial PSG layer by a buffered hydrofluoric (HF) etchant. Scanning electron microscope (SEM) images of the fabricated actuator are shown in Fig. 7.

Initially, Joule heating was used to warm up one of the anchor pads and let the heat being transferred to the actuator by solid thermal conduction mainly. To do so, an electrical circuit was formed across the anchor pad alone without having any current flowing through the structure of the actuator. This setup permitted to electrically control the temperature and the amount of energy applied at the anchor pad according to the Lenz-Joule law.

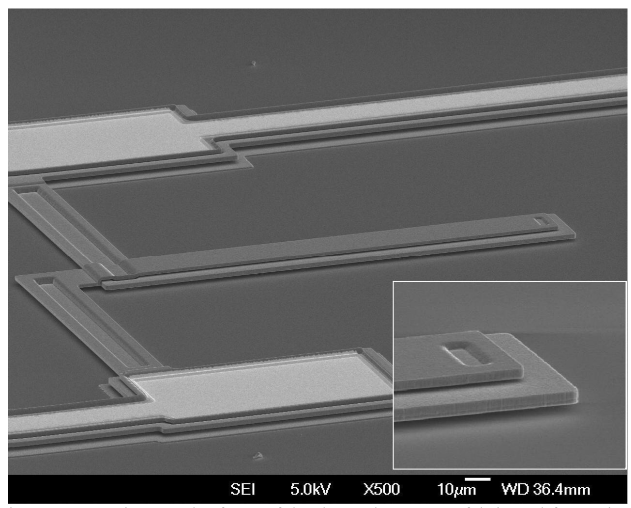


Fig. 7. SEM micrograph of one of the thermal actuators fabricated for testing.

A power supply unit and a source meter were used to provide the current and monitor the voltage simultaneously. A second experimental setup using an electric heating resistor connected to a thermometer was employed to raise the temperature of the substrate of the whole microchip and actuate the devices by pure heat conduction.

Fig. 8 shows the experimental results for displacement as a function of pad temperature. It is worth mentioning that the maximum displacement in the direction of the substrate is limited by the height of the actuator from the substrate which in this case is equal to 2-µm as can be appreciated in the bottom-right inset of Fig. 7.

It can be observed that sufficiently large displacements, useful for many practical applications, are achieved by direct heating of the actuator pad. This is an indication of the feasibility to implement these thermal actuators in many situations where an external heat source is readily available.

The frequency response of the actuator was determined by alternately applying and ceasing to apply the heat source to one of the anchor pads. The main heat dissipation mechanisms are convective heat transfer from the top surface and heat conduction from the bottom surface through the air to the substrate. The contribution of radiative heat transfer may be neglected due to its minimal contribution as stated in section III. Experimentally, it was found that the thermal actuator can operate at a frequency of up to 22-Hz while still displaying full-swing deflection. Thermo-mechanical efficiency and frequency response strongly depend on how the heat is applied to the actuator and on the conditions for heat dissipation. While in some cases the substrate can act as a heat sink, in some others heat dissipation and cyclical operation could be improved by releasing the actuator from its original substrate (e.g. by means of flip-chip, etc.) and transferring it onto a better heat sink that may be part of a more elaborated microsystem involving several mechanisms to transfer the energy from one component to another and obtain useful work.

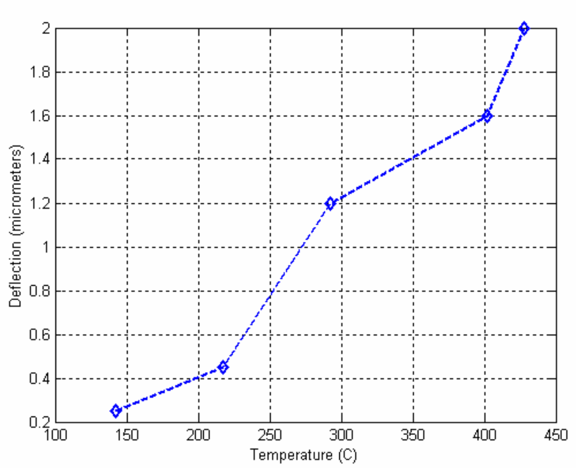


Fig. 8. Displacement of the actuator tip as a function of pad temperature in the direction to the substrate.

## V. Conclusions

A novel vertical thermal actuator device which can be manufactured using a cost-effective standard fabrication process has been introduced. As an alternative to the electrically driven thermal actuators, this design has been optimized for its usage with an external heat source that opens the possibility for energy scavenging.

Actuation of the proposed VTA can be achieved through a variety of means, from the typical Joule heating process to direct bulk heating of the actuator structure. Practically, any source of heat producing a temperature change in the material can be used; heat may be the result of combustion, solar radiation, laser, hot air, geothermal or nuclear energy, direct conduction from a hot surface, etc.

Temperature distribution and thermo-mechanical analysis and modeling have been undertaken. Experiments show that fairly large and useful displacements can be achieved at relatively low operating temperatures. Thermal to mechanical energy conversion has a broad range of practical applications including sensors and actuators for complex electronic systems and MEMS devices.

## Acknowledgments


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## References


[1] H. Guckel, J. Klein, T. Christenson, K. Shrobis, M. Landon and E.G. Lovell, “Thermo-magnetic metal flexure actuators” Proc. of IEEE Solid-State Sensor and Actuator Workshop pp 73–5, 1992.

[2] Q. Huang and N. Lee, Analysis and design of polysilicon thermal flexure actuator, J. Micromech. Microeng. 9, 64-70, 1999.

[3] N.D. Mankame and G.K. Ananthasuresh, Comprehensive thermal modeling and characterization of an electro-thermal-compliant microactuator, J. Micromech. Microeng. 11 452-62, 2001.

[4] D. Yan, A. Khajepour and R. Mansour, Modeling of two-hot-arm horizontal thermal actuator, J. Micromech. Microeng. 13 312–322, 2003.

[5] J.H. Comtois and V. M. Bright, “Applications for surface-micromachined polysilicon thermal actuators and arrays”, Sensors and actuators, vol. A (58), pp. 19—25, 1997.

[6] W. D. Cowan and V. M. Bright, "Vertical thermal actuators for micro-opto-electro-mechanical systems", Proc. SPIE, vol. 3226, pp. 137-146, 1997.

[7] D. Yan, A. Khajepour and R. Mansour, Design and Modeling of a MEMS bidirectional vertical thermal actuator, J. Micromech. Microeng. 14 841–850, 2004.

[8] J.H. Lau, Flip chip technology, McGraw-Hill, New York, 1995.

[9] H. Fu et al., A One-Dimensional Model for Heat Transfer in Engine Exhaust Systems, SAE Technical Paper 2005-01-0696.

[10] Y. Cheng et al., Thermal Analysis for Indirect Liquid Cooled MultiChip Module Using Computational Fluid Dynamic Simulation and Response Surface Methodology, IEEE Trans. Comp. Packag. Technol., vol. 29, no. 1, pp. 39-46, March 2006.

[11] C.JM. Lasance and R.E. Simons, Advances In High-Performance Cooling For Electronics, Electronics Cooling, November 2005. Available on-line at: www.electronics-cooling.com/articles/2005/2005_nov_article2.php

[12] R. Hickey, M. Kujath and T. Hubbart, Heat Transfer Analysis and Optimization of Two-beam Microelectromechanical Thermal Actuators, J. Vac. Sci. Technol. pp. 971, 2002.