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Letter to the Editor

Design of MEMS vertical–horizontal chevron thermal actuators

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ABSTRACT

This paper reports on the first investigation to design, build and characterize a dual vertical and horizontal microactuator based on the topology of a thermal chevron actuator. The chevron-based vertical actuator displays superior performance in comparison to existing electrostatic and electrothermal vertical actuators. The device has the capacity to produce linear vertical motion without deformation of the upper beam surface and is well suited for a variety of optical and microassembling applications. A methodology that may extend the capabilities of standard surface micromachining MEMS technology to design three-dimensional structures is also presented.

1. Introduction

Vertical actuators are useful for many applications requiring out-of-plane displacements. Such applications include tunable parallel plate capacitors and other passive components, optical modulators, RF and optical switches, micromanipulators, etc.

The drawback with existing electrostatic and thermal vertical actuators is that they either require large actuating voltages – incompatible with CMOS electronics – or that their displacement describes a bending trajectory instead of a linear movement which is usually preferred in MEMS systems [1,2].

Also current vertical actuators, including electrostatic and thermal ones, have limited output forces per unit area that are often insufficient for applications like mirror alignment and microassembling tasks. While these actuators typically exhibit forces ranging from just tenths to hundreds of μN/mm^2, horizontal buckle-beam-arrays can develop forces in the order of mN/mm^2 [3,4].

To overcome the limitations of traditional vertical microactuators, a new device is herein proposed based on the architecture of the buckle-beam or chevron thermal actuator. This new device incorporates the benefits of a chevron actuator in terms of high output force, low operating voltages, sub-micrometer resolution in stroke positioning, linear movement without deformation of the shaft, etc.

2. Design concept

Generally speaking, chevron-type electrothermal actuators use an array of silicon beams facing each other in pairs to generate one-directional stroke. Heating of the beam-pairs causes them to expand and ultimately buckle. The beams are designed with a pre-bend angle α, so buckling has a tendency to move in-plane (parallel to the substrate) as depicted in Fig. 1.

Chevron actuators are typically operated via Joule heating. The deflection of the chevron depends on the pre-bending angle α, and the length of the beams L as given by [3]:

$$\mathrm{Def}_{\mathrm{chev}} = [L^2 + 2L(\Delta L) - L\cos^2(\alpha)]^{1/2} - L\sin(\alpha) \quad (1)$$

where L is the length of a single beam, ΔL is the elongation of the beam due to thermal expansion, and α is the pre-bending angle.

Historically, the potential displacement of a chevron actuator in the vertical direction has been considered as an undesirable side-effect and some measures have been proposed to prevent such actions from occurring like the mechanical boundaries described in [3]. Yet, in the case of the classical chevron actuator, the vertical displacement of the device is negligible due to the mechanical constraints imposed by the use of constant-width beams and pre-bending angle α and there is no need for additional artifacts to confine the motion within the horizontal plane.

However, the potential out-of-plane dislocation of the actuator could be exploited to design thermal microdevices capable of producing displacement in both horizontal and vertical axis. This kind of combined vertical and horizontal movement is desirable in many microassembling tools where lifting and pushing are necessary for the alignment of micromirrors, manipulation of small objects, and others. Particularly interesting is the idea of a chevron actuator optimized for out-of-plane vertical displacement alone. This kind of vertical microactuator may be realized by designing the beams with an angle of zero degrees on the horizontal plane ($\alpha = 0$) and just leaving an angle θ formed over the vertical plane as shown in Fig. 2. Such a vertical actuator can benefit from the high output force and linear displacement provided by the chevron topology.

Due to the way in which the actuators are manufactured and then released using surface micromachining processes, a parasitic angle θ is usually formed between the beams and the horizontal plane as shown in Fig. 2. In the following section, some techniques that enable the designer to manipulate the magnitude of the vertical angle θ in a standard two-dimensional manufacturing process are presented.

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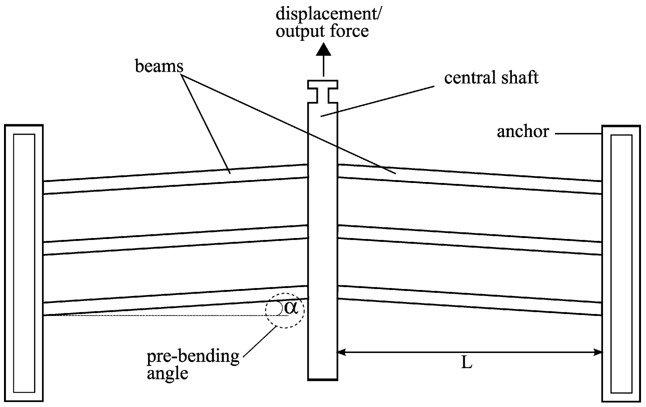

Fig. 1. Chevron-type horizontal thermal actuator.

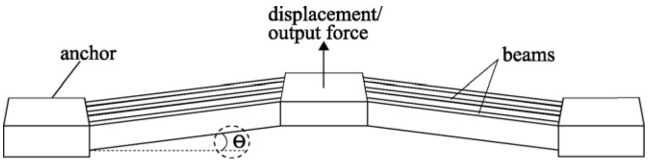

Fig. 2. Modified chevron actuator illustrating the vertical actuating principles.

The electrothermal analysis and modeling used in this research incorporates works by Huang and Lee [5] and Yan et al. [6]. The basis for the operation of a MEMS thermal actuator consists in increasing its temperature to cause the structural material to expand and generate deflection when the device is mechanically constrained.

The complete thermo-mechanical analysis of a heated MEMS actuator is discussed in [5,6,8]. Once the thermal distribution along the microstructure and the resulting elongation are calculated, mechanical deflection of the actuators can be estimated by analyzing the bending moments using some of the methods presented in [6,7]. To first-order, the approximation given in Eq. (1) remains valid for predicting the displacement of the actuator in the vertical direction.

3. Fabrication processing

Table 1
Layer name and thickness in Poly-MUMPs process.

Material layer	Thickness (μm)
Nitride (silicon nitride)	0.6
Poly-0 (non-releasable)	0.5
Oxide-1 (phosphosilicate glass)	2.0
Poly-1 (releasable)	2.0
Oxide-2 (phosphosilicate glass)	0.75
Poly-2 (releasable)	1.5
Metal (gold)	0.5

All devices discussed in this paper were designed for fabrication in the standard multi-user MEMS processes (MUMPs) [9]. MUMPs offer three layers of polysilicon and two sacrificial layers of phosphosilicate glass on an insulating film of silicon nitride. The last two polysilicon layers are releasable. A gold layer can be evaporated onto the surface at the end of the process by low pressure chemical vapor deposition. The thickness of each material film is summarized in Table 1. After construction, the sacrificial layers are removed in a bath of buffered HF acid.

Most MEMS surface micromachining fabrication processes are coplanar processes where the topography of the upper layers depends on the patterns of structural and sacrificial layers underneath. Although sacrificial material is ultimately removed to release the functional structures, the structural layers will maintain the form previously imposed by the presence of the sacrificial matter. As an example, consider the case of a classical chevron actuator fabricated with MUMPs technology. Fig. 3 illustrates how an intrinsic pre-bending angle θ is produced in the vertical plane due to the presence of the first sacrificial oxide under the beams and central shaft.

Some ways to manipulate the vertical pre-bending angle, θ, as a mean to control the amount of displacement of the actuator (by design) may include the use of dummy structures placed beneath the shaft to increase its height. Once the sacrificial oxide layers are removed, these dummy structures will not play any role in the operation of the actuator and can be removed if desired. This technique is illustrated in Fig. 4 where a dummy pattern of Poly-0 is placed below the central shaft of the actuator. Another approach involves a combination of dummy structures to increase the height of the actuator shaft with respect to the anchors and the use of different arrangements of polysilicon layers to form the beams and the anchor pads as shown in Fig. 5.

The ability to increase the height of the central shaft relative to that of the anchors along the same material layer provides the MEMS designer with an extra degree of freedom to work in three-dimensional configurations. Note that Eq. (1) assumes ideal straight beams as in the simplified depiction of Fig. 2. However, since the

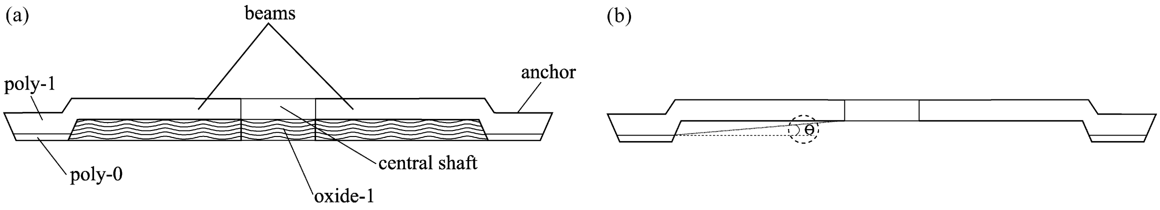

Fig. 3. (a) Approximate cross-sectional shape for the construction of a typical chevron actuator. (b) Cross-sectional view after HF etching of sacrificial layers.

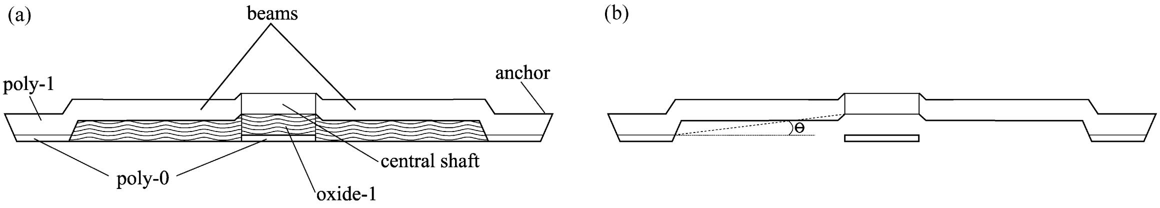

Fig. 4. (a) Approximate cross-sectional shape of a chevron actuator using a Poly-0 dummy pattern under the central shaft. (b) Cross-sectional view after HF etching of sacrificial layers illustrating the vertical angle θ.

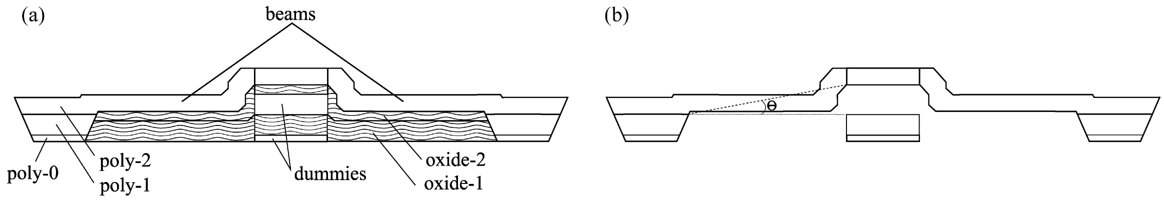

Fig. 5. (a) Approximate cross-sectional shape of a chevron actuator using Poly-0 and Poly-1 dummy patterns under the central shaft. (b) Cross-sectional view after HF etching of sacrificial layers illustrating the vertical angle θ.

Table 2
Summary of dimensions for three different test vertical thermal actuators.

Case	Configuration under central shaft	Length of beams (μm)	Layer of beams	Number of beams	Angle α (°)	Angle θ (°)
1	Oxide-1	200	Poly-1	8	2.3	2.0
2	Oxide-1	200	Poly-1	8	0	2.0
3	Dummy Poly-0 + oxide-1	200	Poly-1	8	0	2.5

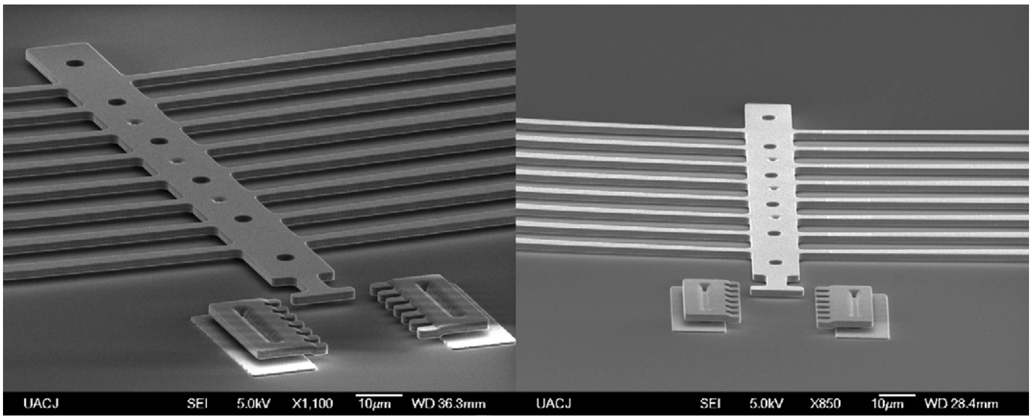

Fig. 6. SEM images of two of the fabricated actuators.

actual cross-sectional geometry of the beams does not form straight lines but a stair-like shape instead (as in Figs. 4 and 5), a deviation from the deflection predicted in Eq. (1) is to be expected.

4. Experimental characterization

A number of test chevron actuators were fabricated using the commercial multi-user MEMS process (PolyMUMPs). In the interest of brevity, only three of the most representative cases will be covered. The basic geometric parameters of three of the fabricated chevron actuators are identified in Table 2. Fig. 6 offers some micrographs of the fabricated micro-actuators corresponding to the configuration of case 1 as listed in Table 2. Measurements were performed using a test setup similar to the one presented in [1] and with the aid of an image processing software.

In all cases, the width of the beams was contoured; i.e. the width of the beams was designed to be thinner at the ends and incrementally thicker until the middle section reaches a width that is about 2.5 times that of the slender sections at both ends. This modification to the shape of the beams improves the thermo-mechanical performance by relaxing mechanical constraints at the joints, reducing stored elastic energy and enhancing flexibility. Beam contouring can be appreciated in the prototypes of Fig. 6. In turns, Fig. 7 presents the experimental results for displacement of the modified chevron actuators of Table 2.

The results demonstrate that chevron thermal actuators can be optimized for realizing vertical motion. It was observed that the narrower beam width at the joints due to contouring not only eases the displacement of the actuator in the horizontal plane when a pre-bending angle α exists, but also facilitates the dislocation in the vertical direction in favor of the intrinsic pre-bending angle θ.

In the situation where both angles (α and θ) are non-zero such as in the device of case 1 from Table 2, the net result is that the shaft of the actuator moves in two directions at the same time, i.e. the actuator performs compounded displacement composed of a vector in the horizontal axis and another vector in the vertical

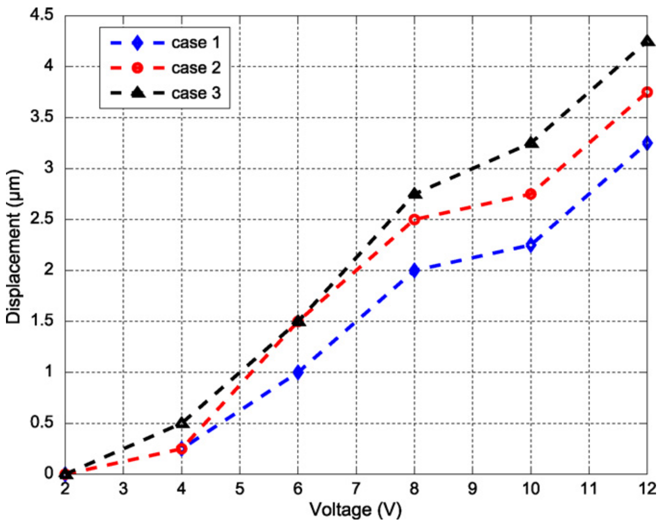

Fig. 7. Displacement along the vertical axis as a function of voltage for the three tested chevron prototypes.

one. In principle, the input energy is split to actuate the device in two directions at a time and the peak in-plane and out-of-plane displacement is a function of the applied voltage and the magnitude of the pre-bending angles in each direction.

5. Conclusions

The feasibility of implementing vertical thermal actuators based on the chevron topology has been confirmed. These kinds of devices offer a number of advantages over traditional electrostatic and thermal vertical actuators comprising CMOS-voltage compatibility, high actuating forces, linear vertical motion of the central shaft without deformation or bending, etc.

The design of vertical chevrons leverages the coplanar nature of standard surface micromachining processes to produce forms and angles on a third dimension. While most of the art in MEMS electro-thermal actuators is only capable of generating single degree-of-freedom motion, the chevron actuator described in this work has the ability to generate displacement in both the horizontal and vertical planes.

Applications for these vertical actuators include widely tunable capacitors for RF filters with low driving voltage, optical modulators and optical switches without deformation of the mirror surface, 3D reflective spatial light modulators and servo-scanning applications where continuous scan ranges and position control are required, microassembling and micromanipulation, etc.

References

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

[2] H. Zhu, et al., Design and fabrication of reflective spatial light modulators for high-dynamic-range wavefront control, Proc. SPIE 5553 (2004) 39–45.

[3] M.J. Sinclair, A high force low area MEMS thermal actuator, in: Proceedings of Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, 2000, pp. 127–132.

[4] W. Chen, C. Wu, C. Lee, Bi-directional movable latched micromechanism using one-directional movable chevron electrothermal actuators for switch and relay applications, Microproc. Nanotech. Conf. (2003) 180–181.

[5] Q. Huang, N. Lee, Analysis and design of polysilicon thermal flexure actuator, J. Micromech. Microeng. 9 (1999) 64–70.

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

[7] N.D. Mankame, G.K. Ananthasuresh, Comprehensive thermal modeling and characterization of an electro-thermal-compliant microactuator, J. Micromech. Microeng. 11 (2001) 452–462.

[8] R. Hickey, M. Kujath, T. Hubbart, Heat transfer analysis and optimization of two-beam microelectromechanical thermal actuators, J. Vac. Sci. Technol. 20 (3) (2002) 971–974.

[9] J. Carter, et al., PolyMUMPS Design Handbook, MEMSCAP Inc., Revision 11.0, 2005.

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