A Bi-directional Electrothermal Actuator with Z-shaped Beams

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Abstract—A bi-directional micro-actuator powered by electrothermal force is successfully demonstrated under both dc and ac operations without the assistance of magnetic field using MetalMUMPs process. To achieve small stiffness without buckling, which tends to occur in V-shaped actuators, a new Z-shaped electrothermal actuator is designed. With the actuation current from -13 mA to +13 mA, the electrothermal actuator can achieve a bi-directional motion in a dynamic range of -11.6 μm to +12.8 μm . Experimentally obtained frequency response of the actuator indicates that it has a bandwidth of 49 Hz.

Index Terms—Electrothermal Actuator, Bi-directional Motion, Microsystem Design.

Micro-actuators are essential components in MEMS devices for producing physical motion at the micro and nanometer scales. Various micro-actuators have been demonstrated in the literature using different operation principles such as electrostatic, electrothermal, electromagnetic, and piezoelectric effects [1]. Among them, the electrostatic actuators are most commonly used due to their high energy efficiency, large response bandwidth, and bi-directional motion capability. However, to simultaneously achieve a large displacement and a high force, a rather large actuator footprint is required, which may not practical in applications in which space is limited. Furthermore, the yield of large overlapping areas and compliant suspension structures could be fairly low due to stiction and/or failure between two electrostatic plates.

In contrast, electrothermal actuators have been demonstrated to be compact, stable, and high-force devices under low actuation voltages [2]. The actuation is based on the thermal expansion of the actuation beams caused by Joule heating. Usually, the heating is achieved by passing current through the beams to cause resistive heating. The dimension is small but the displacement can be mechanically amplified, for example, by using V-shaped or Chevron shaped beams. This type of electrothermal actuator has been widely used due to its

small footprint, high force (on the order of mN), and reasonable large motion (on the order of 10 μm). However, V-shaped electrothermal actuators beams possess an extremely high mechanical stiffness when forced against their direction of operation, rendering them unsuitable for bidirectional motion. A mono-directional electrothermal actuator has limited operational motion range, which is half of its bi-directional counterpart. And it is not practical and stable enough for some applications, e.g. actuation of a nanopositioning stage [3]. A bi-directional electrothermal actuator has been reported in [4]. However, to achieve bi-directional operation, it must be placed in a magnetic field.

In this letter, we introduce and experimentally demonstrate a new type of electrothermal actuator, which has bi-directional capability. Two flexible Z-shaped beams are connected back-to-back to achieve bidirectional actuation without buckling in V-shaped beams. Experimental results illustrate that this bi-directional actuator can move from -11.6 μm to +12.8 μm when applying -13 mA to +13 mA actuation current and with a bandwidth of 49 Hz. The bi-directional nature of this device and its ability to accurately move within its displacement range, may lead to interesting possibilities in microsystem design.

I. DESIGN

Fig.1. Working principle of the bi-directional electrothermal actuator with Z-shaped beams. Schematic (a) and cross-section view (b) of the actuator.

As illustrated in Fig.1, a Z-shaped actuation beam was adopted for this electrothermal actuator. The actuators are powered by clamped-clamped Z-shaped beams, which are fixed between two bonding pads. As electrical current flows through a beam, joule heating causes it to expand. The beam's

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Z shape translates the expansion into mechanical motion in a specific direction. This kind of electrothermal actuation can achieve force and displacement comparable to its V-shaped counterpart [5].

To avoid the signal mixing between the two actuation currents, an indirect-heating method was utilized. The Z-shaped metal beams were heated by poly-silicon heaters through the 1.1 μm air gap. As shown in Fig.1, the bi-directional actuator consists of four Z-shaped Nickel beams. Each beam is 500 μm long and 8 μm wide, with a 10 μm short vertical beam in the middle. A movable 60 μm ×560 μm central shuttle connects the Z-shaped beams in the middle. The heater is made of poly-silicon layer and is located underneath the nickel beams. The heater has a snake shape with 30 μm width and 2000 μm total length.

Fig.2. (a) The finite element method (FEM) simulation results using CoventorTM, showing the downward deformation of the bi-directional actuator; (b) SEM photo of the fabricated bi-directional actuator.

When the current flows through the upper poly-silicon heater, the resistive heating will increase the temperature of nickel beams due to the thermal conduction through air. The upper Z-shaped beam will deform to the upward direction, and the bottom beam actuator will follow in the same direction. Similarly, the central shuttle will move down when applying current through bottom actuator, as shown in the CoventorTM finite element method (FEM) simulation results in Fig. 2(a).

II. EXPERIMENTAL RESULTS

The electrothermal actuator proposed in this paper was micro-fabricated using MEMSCAP's Metal Multi-User MEMS Process (MetalMUMPs). MetalMUMPs offers two structure layers of 20 μm electroplated Nickel and 0.7 μm poly-silicon. Between these two layers there exists an air gap of 1.1 μm , which enables the layers to move relative to each other. The poly-silicon layer is sandwiched between two 0.35 μm silicon nitride layers. The SEM photo of fabricated device is shown in figure 2(b).

The fabricated device was actuated by applying the actuation current through the poly-silicon heater. The dc and ac displacement responses were measured using a PolytecTM Planar Motion Analyzer (PMA-400, Polytec GmbH). Digital image capturing and analysis methods were used to determine the in-plane displacement of the actuator.

Fig.3. (a) Measured displacement as a function of input current; (b) Measured displacement as a function of applied frequency, indicating a bandwidth of 49 Hz.

Fig.3 (a) plots the static actuation current vs. displacement. With the actuation current from -13 mA to +13 mA, the electrothermal actuator can achieve bi-directional motion in a dynamic range of -11.6 μm to +12.8 μm . Fig.3 (b) illustrates the frequency response of the bi-directional electrothermal actuator. The results show that the open-loop bandwidth of the actuator is 49 Hz, which is relatively low compared to the thermal structures fabricated using PolyMUMPs process [4]. The reason is believed to be due to the fact that, in MetalMUMPs, heat transfer to the surrounding air is much slower than to the substrate in PolyMUMPs

III. CONCLUSION

The paper reported a novel electrothermal micro-actuator, which can move bi-directionally in a plane by applying actuation current through the poly-silicon heater. Experimental results from a micro-fabricated actuator using the standard MetalMUMPs process validated the bi-directional operation with a dynamic range of more than 20 μm . Bi-directional actuation is expected to have double dynamic range than widely used homo-directional V-shaped electrothermal actuation, and may lead to interesting possibilities in microsystem design.

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