A Novel Single-layer Bi-directional Out-of-plane Electrothermal Microactuator

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ABSTRACT
In this study, a novel bi-directional out-of-plane electrothermal actuator is designed and fabricated. Unlike the bi-metal and hot-cold arm thermal actuator, this actuator can move in two directions. Since this actuator is consisted of only single layer thin film material, it can prevent from delamination. According to the static load-deflection test, this actuator can achieve bi-directional actuation with amplitude near several microns when driven at 5V. According to the vibration test, the dynamics of the actuator is influenced not only by the thermal characteristics but also by the vibration modes. Consequently, the thermal actuator still has a significant output when driven near 40 kHz. The actuator were experienced a fatigue test which shows that its resonant frequency remains unchanged after \(10^4\) cycles of continuous operation with driving voltage at 2.25 Vpp.

Key words: Thermal actuator, out-of-plane motion, delamination, fatigue test

INTRODUCTION
Microactuator is one of the key components for MEMS devices. According to the motion of the actuators, they can be categorized as in-plane actuator [1] and out-of-plane actuator [2]. The out-of-plane actuators can convert input signals into displacement normal to the surface of a silicon wafer. They accordingly have many applications, for instance the optical scanner, optical switch, micro relay, variable capacitor, and so on. There are various approaches, such as magnetic, electrostatic, electrothermal, and piezoelectric, have been employed to drive the out-of-plane actuators. The electrothermal actuators have the advantages of low operation voltage, simple fabrication process and CMOS-compatible. They have been exploited to drive various MEMS devices [3-6]. In this study, the electrothermal out-of-plane actuator is discussed.

The existing out-of-plane thermal actuators are usually multi-layer structures. For instance, the bi-layer electrothermal actuator employed the bimorph effect to generate out-of-plane motion. Such a bi-layer actuator comprises two materials which coefficients of thermal expansion differ from each other. The application of a temperature-change stimulus would thus give rise to out-of-plane displacement since the expansions of both layers are different. As a second example, Bright presented a multi-layer electrothermal actuator consisted of only a single material. The actuator comprised a few beams of different cross-sectional areas. While a current is applied, different deflection of beams accompanying temperature rise caused out-of-plane motion [7-8]. However, these multi-layer actuators experience a shear force at the interface of different layers, while actuated. Delamination consequently would take place after a long-term operation and consequently decreases its lifetime. In addition, these actuators can only bend in one direction while heating.

To fabricate electrothermal actuator using a single-layer structure has been presented in [8-9]. The single-layer actuator consists of a narrower “hot” arm and a wider “cold” arm. The different thermal expansion between the hot-arm and the cold-arm will lead to an in-plane displacement of the actuator. Thus, the in-plane motion of the actuator is mainly due to the geometry design of the structure instead of material property of thin film. In attempt to overcome the drawback inherent in a multi-layer actuator, an out-of-plane electrothermal actuator of single-layer structure is presented in [10]. This single-layer out-
of-plane actuator also consists of a narrower “hot” arm and two wider “cold” arms. The different thermal expansion between the hot-arm and the cold-arms will lead to an out-of-plane displacement of the actuator. In this design, the performance and reliability of the actuator is limited to the thinner hot-beam. A novel single-layer out-of-plane electrothermal actuator is investigated in this study. Since this actuator is consisted of only single layer thin film material, it can prevent from delamination. Moreover, the structure is designed to allow bending upwards as well as downwards in the out-of-plane direction. Hence, this actuator can move in two directions, unlike the existing thermal actuators. The performance and reliability of the presented design was demonstrated in light of finite element analysis and experimental results.

DESIGN AND ANALYSIS

The presented actuator comprises four parallel, identical beams, as illustrated in Fig. 1a. These four beams are connected with a connecting arm at their free ends and then formed a single-layer thermal actuator. Since the inner beams and the outer ones are located at different planes, there are two steps at the free ends of the former ones. While a current only flows through the inner beams, they would experience a higher temperature rise as well as a larger thermal expansion. The beams are not coplanar, a larger thermal expansion on the inner beams would give rise to a torque, so as to induce an upward out-of-plane motion. On the contrary, while a current only flows through the outer beams, the actuator would experience a downward out-of-plane motion. The bi-directional out-of-plane motion is thus achieved. Since this actuator is consisted of only single-layer thin film material, the delamination problem can be prevented. Moreover, beams of the actuator have identical width, the disadvantage caused by the localization of higher temperature at the thinner beam in [10] can also be prevented.

The design was examined using commercial finite element software. In order to compare with the experimental results, the thin film material and substrate employed in this model is single crystal silicon. The material properties used in the FEM model are as follows, Young’s modulus \( E = 169 \text{ Gpa} \), coefficient of thermal expansion \( \text{CTE} = 2.5 \times 10^{-6} \) (at 300°C) and \( 4.3 \times 10^{-6} \) (at 800°C), thermal conductivity \( K_p = 157 \text{ W/m°C} \), specific heat \( S = 702.24 \text{ J/Kg°C} \), and resistivity \( \rho = 1.1 \times 10^{-5} \text{ Ω-m} \). In addition, various critical dimensions of the actuator including length \( L \), width \( W \), and thickness \( t \) of the beams, length \( L_c \) and width \( W_c \) of the connecting arms, and height \( h \) of the step, are indicated in Fig. 1b. The bending of the thermal actuator caused by the applying voltage was discussed. In addition, the temperature distribution of the actuator during operation was also studied. Consequently, the characteristics of the thermal actuator can be predicted.

Figure 2 shows the typical simulation results on a thermal actuator. In the simulation, the critical dimensions of the beams and connecting arms are as follows, \( L = 240 \mu\text{m} \), \( t = 2 \mu\text{m} \), \( W = 10 \mu\text{m} \), \( L_c = 10 \mu\text{m} \), \( W_c = 10 \mu\text{m} \), and \( h = 2 \mu\text{m} \). A typical simulation results regarding the deflection and temperature distribution of an actuator is shown in Fig 2. In this case, the actuator was applied with 5V driving voltage at its inner beams. As shown in Fig. 2a, the temperature is distributed between 200°C to 1300°C. As shown in Fig. 2b, the temperature distribution of the inner beams and outer beams are depicted quantitatively. Since there is no current pass through the outer beams, they will only conduct the heat generated by the inner beams to the substrate. Thus, the temperature of the outer beams is decreased linearly from their tip to the ends. Since there is heat conduction from the connecting arm to the outer beams, the highest temperature of the actuator in this case will not occur at the tip of the inner beams. In general, the highest temperature region of the actuator is about a quarter away from the tip of the driving beams, according to the simulation. As shown in Fig. 2c, the deflection amplitude at the tip of the actuator is near 10μm upwards.
EXPERIMENT AND RESULTS

In order to demonstrate the concept proposed in this study, the actuator was fabricated and tested. The fabrication processes that contain three masks are illustrated in Fig. 3. As shown in Fig. 3a, the silicon substrate was etched first to define the height \( h \) of the step. Heavily doped boron was exploited to define the structure of the actuator, as indicated in Figs. 3b–c. The silicon substrate bulk etching was conducted to release the actuator after the thermal oxide etching mask was patterned, as shown in Figs. 3d–f. Consequently, the actuator was formed by the single-layer boron doped silicon.

The test apparatus are illustrated in Fig. 4. To compare with the analytical results, the test was mainly focused on a 240 \( \mu \)m long, 10 \( \mu \)m wide, and 1.2 \( \mu \)m thick actuator. The static deformation of the micro actuator was measured by the interferometer. The actuator was driven by a DC signal from power supply, and the out-of-plane deformation of the beams can be measured by a non-contact optical interferometer. Two typical results measured when the actuator was driven upward and downward are shown in Fig. 5. It demonstrates that the thermal actuator can be operated bi-directionally. The triangle dots in Fig. 6 represent the measured tip deflection under various driving voltages. Thus, the variation of the driving voltage and the deflection of the actuator is determined. It also shows that the actuator has an upward deflection amplitude near 7.5 \( \mu \)m when driven at 5V, however, the downward deflection amplitude drops to 6 \( \mu \)m at the same driving voltage. Moreover, the highest temperature region can be
Fig 7. The photos take from a CCD camera to show the highest temperature region on the actuator when the driving voltage is (a) 6.5V, (b) 6.7V, and (c) 6.85V qualitatively observed using CCD camera, as indicated in Fig. 7. These photos show an actuator operating at 6.5V, 6.7V, and 6.85V, respectively. The brightest region in the photos indicates the area with the highest temperature. It is obtained that the highest temperature region predicted by the simulation in Figs. 2a-b agrees well with the observation from CCD camera.

The dynamic response of the micro actuator was measured by the Laser Doppler Vibrometer (LDV). In this case, the actuator was driven by an AC signal from function generator. Figure 8a shows the frequency response of the actuator when applying voltage ranging from 1 Vpp to 4 Vpp. The frequency response of the actuator has two peaks. The first peak has a very wide bandwidth, and locates near 1.9 kHz regions. The second peak has a narrow bandwidth, and locates near 36 kHz regions. A vibration test on the structure of actuator is also conducted using an external piezoelectric shaker. In this experiment, the measured frequency response in Fig. 8b shows the dynamic characteristics of the structure of the actuator. Apparently, the first vibration mode of the actuator is at 36.2 kHz. The vibration test demonstrates that the second peak in Fig. 8a corresponds with the nature frequency of the actuator. Consequently, the first peak of the frequency response is due to the thermal characteristic of the actuator. According to the measurement results, the actuator still has 2.2 μm out-of-plane deflection amplitude even when operation with a 2Vpp (peak to peak voltage), and 36 kHz sinusoidal wave signal.

The fatigue test was also conducted in this experiment. In this test, the thermal actuator was applying with 2.25 Vpp and 33 kHz sinusoidal voltage. Typical fatigue test results are available in Fig 9. As shown in Fig. 9a, the resonant frequency of the actuator has only 0.3% deviation after 10^6 cycles continuous operation. As shown in Fig. 9b, the vibration amplitude of the actuator remains at 2.36μm for 10^7 cycles continuous operation. The vibration amplitude start to drift and drop to 2.06μm for 10^5 cycles.

Fig 8. The frequency response of the actuator when it is driven by (a) electrothermal approach, and (b) external piezoelectric shaker approach.

Fig 9. Typical fatigue test results of the actuator, (a) resonant frequency and (b) vibration amplitude versus the test cycles.
continuous operation, after that it will increase to 2.34μm for 10⁹ cycles continuous operation.

**DISCUSSION AND CONCLUSION**

A novel single-layer out-of-plane electrothermal actuator is designed and fabricated in this study. The thermal actuator is fabricated through the bulk micromachining processes. Unlike the bi-metal and hot-cold arm thermal actuator, this actuator can move in two directions. The load-deflection test demonstrates that this actuator can achieve bi-directional actuation with amplitude near 6–7.5 μm when driven at 5V. This characteristic enables the thermal actuator to perform as a bi-directional positioner. The vibration test shows that the thermal actuator still has a significant output when driven near 40 kHz. This characteristic enables the thermal actuator to perform as a resonant actuator. Since the proposed thermal actuator is consists of only single-layer thin film material, it can prevent from delamination and its lifetime is significantly improved. The actuator were experienced a fatigue test which shows that its resonant frequency remains unchanged after 10⁹ cycles of continuous operation with driving voltage at 2.25 Vpp.

The cross dots in Fig. 6 represent the simulated tip deflection under various driving voltages. It is obtained that the trend of the simulation results is similar to that of the measured ones. However, the maximum deviation between the measured and simulated results is 71% for the upward case and 54% for the downward one. The primary error source comes from the contact resistance between the probe tip and the bonding pad during experiment. Thus the measured displacement is smaller than the predicted one. The driving voltage for the experiment can be modified by considering the contact resistance, as indicated by the circular dots in Fig. 6. Thus the maximum deviation between the measured and simulated results drops to 35% for the upward case and 5% for the downward one. This problem can be further improved by using the wire bond instead of the probe tip during experiment. Another potential error source is the ignorance of the variation of resistivity due to temperature change in the simulation model. Hence, the deviation between simulated and measured results is larger at high temperature regions.

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