Effects of Sidewall Inclination on Performance of Electrothermal Micro-Actuator

Siru Teng, Chunhua Cai
Jiangsu Key Laboratory of Power Transmission & Distribution Equipment Technology
College of Internet of Things, Hohai University, Nanjing, China

Abstract—As an important part of Micro-Electro-Mechanical systems (MEMS), micro-actuators have a direct impact on the performance of MEMS devices. This paper presents the effects of sidewall inclination of deep reactive ion etching (DRIE) on the performance of U-shaped electrothermal micro-actuators. The electrothermal micro-actuator models with sidewall inclination angles from -5° to 5° are simulated through finite element method (FEM) by ANSYS to study the influences on the output displacement and the highest node temperature. The simulation results show that electrothermal micro-actuator with larger sidewall inclination angle has more displacement deviation. In addition, larger voltage amplifies the deviation of displacement. The highest node temperature decreases with the increase of the sidewall inclination, and the deviation is small.

1. INTRODUCTION
The micro-actuators are important components for various Micro-Electro-Mechanical systems (MEMS) based devices for actuation purposes like micro mirrors [1, 2], resonant [3] and non-resonant gyroscopes [4]. Micro-actuators are MEMS devices that convert electrical signals, thermal energy, optical energy or magnetic energy into micro-actions or micro-operations [5]. According to the actuation mechanisms, there are four main types of micro-actuators: electrostatic actuators, piezoelectric actuators, thermal actuators and electromagnetic actuators [6].

Among these actuation mechanisms, the electrothermal actuation is widely exploited over the past few decades due to advantage of their abilities in producing high output forces and large displacements at lower actuation voltages [7]. U-shaped, V-shaped and Z-shaped configurations are most commonly used for producing in-plane motions. The U-shaped actuator can output high forces with a wide range of displacement compared to other micro-actuators in MEMS. Due to the width of the hot arm and the cold arm are different, after the voltage is applied, the thermal expansion of the two arms are different eventually causing upward deformation to achieve actuation purposes.

To ensure the performance of electrothermal micro-actuators, the fabrication process is essential. Deep reactive ion etching (DRIE) is the standard process to define the geometry of the movable elements for MEMS by utilizing etching and passivation alternate processing technology to obtain high sidewall verticality and higher aspect ratio [8]. This process is directly related with the plasma behavior and can theoretically be evaluated by multi-physical simulation [9].

However, the DRIE etching process may affect the geometry of micro-actuator, and cause poor performance. This situation is encountered during the fabrication of all types of micro-actuators. The typical U-beam structures is selected in this paper. To U-shaped electrothermal micro-actuator, the DRIE
etching process may cause a sidewall inclination [10]. The exact deviation of sidewall inclination angle is crucial since it directly affects the performance of the U-shaped electrothermal micro-actuators.

This paper presents the design and modeling of the U-shaped electrothermal micro-actuator. The output displacement and the highest node temperature generated by the electrothermal micro-actuator is simulated by ANSYS. Moreover, the impact of different voltage on the output displacement and the highest node temperature is also observed based simulations.

2. DESIGN OF THE U-SHAPED ELECTROTHERMAL MICRO-ACTUATOR

Typical U-shaped electrothermal micro-actuator is consisted by hot arm, cold arm and flexure in a folded configuration, as can be seen in figure 1.

![Figure1. U-shaped electrothermal micro-actuator.](image1)

The electrothermal heating of different arms leads to non-equivalent expansions between the two sides of the folded actuator. The slight expansion of these arms is amplified by the structure to generate a considerable displacement at the tip of the actuator.

A three-dimensional finite element method (FEM) model is established by ANSYS and shows the simulation of the structural deformation and the thermal distribution of the actuator after applying electrical voltage. The actuator in the simulation has the same dimensions as in Figure 2.

![Figure2. The modelled micro-actuator’s dimensions.](image2)

3. EFFECT OF SIDEWALL INCLINATION ON THE RESISTANCE AND STIFFNESS OF THE FOLDED BEAMS

Resistance and stiffness are two important factors which affect the performance of U-shaped electrothermal micro-actuator. The output displacement relates to heat and stiffness. It is necessary to study the effect of sidewall inclination to resistance and stiffness.
3.1 Resistance

Due to the sidewall inclination by deep reactive ion etching (DRIE), the cross-sectional area of the folded beams varies. And the resistance of the folded beams changes. According to power formula, $p = \frac{U^2}{R}$, where $p$ is the power, $U$ is the voltage across, $R$ is the resistance in circuit. Resistance is associated with the thermal energy. The thermal energy is important since it directly affects the displacement and temperature of the electrothermal micro-actuator.

![Figure 3. Cross section of micro-actuator excludes sidewall inclination.](image)

![Figure 4. Cross section of micro-actuator incorporates sidewall inclination (angle is positive).](image)

The usual resistance formula given below may be used. In the formula $R$ is the resistance, $\rho$ is the electrical resistivity, $l$ is the length, and $s$ is the cross-sectional area. The resistance of the hot arm and cold arm (Figure. 3), which excludes sidewall inclination, could be expressed as:

$$R = \rho \frac{l}{s}$$

Assuming that the thickness is $t$ and the sidewall inclination angle is $\varphi$. Define the sidewall inclination angle in Figure 4 is positive. The resistance of the hot arm and cold arm, which incorporates the sidewall inclination angle, could be expressed as:

$$R_{\text{side}} = \rho \frac{l}{s - t^2 \tan \varphi}$$

The relative resistance could be expressed as:

$$\frac{R_{\text{side}}}{R} = \frac{s}{s - t^2 \tan \varphi}$$

As is shown in Figure 3, the cross-sectional area of hot arm is significantly less than the cold arm. The sidewall inclination affects more on hot arm. To simplify the question, choose hot arm to calculate. Figure 5 shows the relative resistance (the ratio of two resistance) as a function of sidewall inclination angle $\varphi$ under the conditions of thickness $t = 50 \mu m$, the length of hot arm $l = 2140 \mu m$, the cross-sectional area $s = 2000 \mu m^2$ and the sidewall inclination angle $\varphi$ is in the range $-5^\circ$ to $5^\circ$. The relationship between the angle and relative resistance is nonlinear.
Figure 5. Relative resistance versus sidewall inclination angle.

The curve shows that the relative resistance $\frac{R_{side}}{R}$ increases from 0.9014 to 1.1228 with the sidewall inclination angle in the range from $-5^\circ$ to $5^\circ$.

In this work, the relative resistance is calculated to indicate sidewall inclination influences resistance. The thermal energy changes with resistance, also causing displacement and temperature change.

3.2 Stiffness

Another factor which sidewall inclination affects is stiffness. The larger positive sidewall inclination angle tends to be more reentrant. Consequently, they affect the performances of the U-shaped electrothermal micro-actuator.

Figure 6 Folded-flexure beams with sidewall inclination.

The stiffness in the x-direction of the folded flexure beams $K_X$, which excludes sidewall inclination, is calculated as:

$$K_X = \frac{4EtW^3}{3L^3}$$

where $E$ is the Young’s modulus, $t$ is the thickness of folded flexure beam, $W$ is the beam width and $L$ is the length of one beam segment.

Then the stiffness in the x-direction of the folded beams $K_{X-side}$ is calculated as:

$$K_{X-side} = \frac{12EI}{L^3} \cdot \frac{4}{3}$$

where $I$ is the inertial momentum.

$I_{X-side}$ can be calculated using integration:

$$I_{X-side} = \int_0^L \frac{1}{12} (W + 2z \tan(-\varphi))^3 dz = \frac{(2t \cdot \tan(-\varphi) + W)^4 - W^4}{96 \tan(-\varphi)}$$

The relative stiffness could be expressed as:

$$\frac{K_{X-side}}{K_X} = \frac{(2t \cdot \tan(-\varphi) + W)^4 - W^4}{8 \cdot \tan(-\varphi) \cdot t \cdot W^3}$$
Figure 7 shows the relative stiffness (the ratio of two resistance) as a function of sidewall inclination angle $\varphi$ under the conditions of thickness $t = 50 \mu m$, the beam width $W = 40 \mu m$, and the sidewall inclination angle $\varphi$ is in the range $-5^\circ$ to $5^\circ$. The relationship between the angle and relative stiffness is nonlinear.

![Figure 7. Relative stiffness versus sidewall inclination angle.](image)

The curve shows that the relative stiffness $\frac{K_{X-side}}{K_X}$ decreases from 1.3785 to 0.7171 with the sidewall inclination angle in the range from $-5^\circ$ to $5^\circ$.

In this work, the relative stiffness is calculated to indicate sidewall inclination influences stiffness, then influences the output displacement.

4. EFFECT OF VOLTAGE ON THE DISPLACEMENT AND TEMPERATURE OF THE U-SHAPED ELECTROTHERMAL MICRO-ACTUATOR

The electrothermal actuator works on the principle of Joule heating. According to the power formula, $p = \frac{U^2}{R}$, where $p$ is the power, $U$ is the voltage across, $R$ is the resistance in circuit. The voltage also affects the thermal energy. The effects of excessive voltage will cover the effects of sidewall inclination. A suitable voltage is important.

Simulation is performed by using ANSYS to predict the output displacement and the temperature rise on U-shaped electrothermal micro-actuator in response to the applied voltage. The ideal model and the model with a $5^\circ$ sidewall inclination angle are compared at voltages from 3V to 13V.

4.1 Output Displacement

Figure 8 shows that as the voltage increases, the output displacement of the electrothermal micro-actuator becomes larger. The trend follows $U^2$ as a parabola. And the output displacement deviation caused by the etching sidewall inclination increases with voltage.

![Figure 8. Output displacement versus voltage.](image)
4.2 The highest node temperature

Figure 9 shows that the highest node temperature of an electrothermal micro-actuator increases with increasing voltage. Whether at lower or higher voltages, the electrothermal micro-actuator with etching inclination is almost the same as the ideal model. Through the simulation, the etching inclination has little effect on the highest node temperature of the electrothermal micro-actuator.

![Figure 9. The highest node temperature versus voltage.](image)

5. Effect of sidewall inclination on the displacement and temperature of the U-shaped electrothermal micro-actuator

The electrothermal actuator has been designed according to the parameters given in the Figure 2. 10V and 0V are applied to the anchors of the hot and cold arms respectively. The effect is shown in Figure 10.

![Figure 10. Diagram of electrothermal micro-actuator by ANSYS.](image)

5.1 Displacement

Figure 11 and 12 show the deviation of the output displacement and the highest node temperature as a function of the sidewall inclination angle, under the conditions of thickness \( t = 50 \mu m \), driving voltage \( U = 10 \) V, sidewall inclination angle \( \varphi \) in the range \(-5^\circ\) to \(5^\circ\).

The displacement curves of the actuator with respect to the sidewall inclination angle can be seen in figure. The displacement curves are shown for 10V applied voltage. The result shows that the output increases from 12.5 \( \mu m \) to 14.2 \( \mu m \) with the sidewall inclination angle in the range from \(-5^\circ\) to \(5^\circ\). On the condition that the positive and negative inclination angles are equal, the maximum displacement deviation is similar. The greater sidewall inclination angle (whatever positive or negative) causes the greater displacement.
The results are consistent with the phenomenon that the equivalent resistance of the cold and hot arms is related to size. The sidewall inclination angle changes causing its size changes. Then the equivalent resistance value changes. Different resistance generates different thermal energy, leading to different displacement. According to the simulation result, the effect of sidewall inclination on the displacement of the electrothermal micro-actuator increases with angle.

5.2 The highest node temperature

The simulation result shows the highest node temperature of the electrothermal micro-actuator decreases with the deviation of sidewall inclination angle increases. The highest node temperature takes the maximum value in the ideal situation. The deviation ratio is about 0.1% with the sidewall inclination -5°, only 0.667K. As a result, sidewall inclination has a little effect on temperature of U-shaped electrothermal micro-actuator.

6. CONCLUSION

A design of U-shaped electrothermal micro-actuator to be used for MEMS is proposed in this study. By the simulation in the ANSYS, the impact of various sidewall inclination on the output displacement and the highest node temperature is studied. And the impact of voltage is also studied.

The result shows that the output displacement increases from 12.5 μm to 14.2 μm with the sidewall inclination angle in the range from -5° to 5°. The deviation of output displacement is associated with the deviation of sidewall inclination because sidewall inclination affects stiffness of the flexure arm. The deviation ratio of relative stiffness with the sidewall inclination angle -5° is 37.8%. In addition, voltage amplifies the deviation of displacement. The deviation ratio of highest node temperature with
the sidewall inclination angle -5° is 0.1%. This means the sidewall inclination has little effect on temperature.

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