DESIGN AND SIMULATION OF AN OUT-OF-PLANE ELECTROTHERMAL MICROACTUATOR

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Abstract - Microactuators are one of the most important components in microelectromechanical systems (MEMS). Therefore, designing effective out-of-plane actuators has been in progress for the last decade. This paper presents a novel design of the microactuator with a double stepped beam structure for large out-of-plane deflection output applied to microvalves. The design and analysis of the out-of-plane microactuator are implemented by the finite element method. Silicon is selected as the material of the actuator and the beam motion is generated by the Joule heating effect. Compared to a single stepped beam design reported in the literature, the simulation results show that the proposed double-stepped beam structure can deliver a much larger out-of-plane deflection. Under an applied current of 15 mA, the maximum deflection of the double stepped beam is nearly seven times higher than that of the single stepped beam structure. In addition, the stress analysis indicates that the largest stress (1.46 GPa) induced in the beam is much smaller than the yield strength (7 GPa) of the selected silicon material.

Key words - Double stepped beam; electrothermal; large deflection; microactuator

1. Introduction

Microactuators are micro-scale active devices designed to generate mechanical motion of solids or fluids by converting one form of energy (e.g., electrical, thermal, electrostatic) into kinetic energy. In microelectromechanical systems (MEMS), out-of-plane microactuators have a number of interesting applications such as optical switches, micromirrors, micro-optics, etc [1-4].

Recently, several microscale out-of-plane motion mechanisms have been developed. For instance, Khan et al. [5] designed a repulsive microactuator which can generate an out-of-plane force. Their prototype fabricated by PolyMUMPs process can produce an out-of-plane displacement of 15 μm and a 0.2^{o} angular rotation with the estimated out-of-plane force of 40 μN at 100 V. Atre [6] presented a bimorph out-of-plane motion mechanism using a two-layer structure where a thin arm is located below a wide arm. Bimorph structures have long been studied and used for sensors and actuators because of their sensitivity, fast response time and ease of integration with semiconductor technology. Compared to the stepped beam structure, the bimorph structure adds some complexities to the fabrication process. Moreover, the performance of multi-material microactuators is limited by reduced reliability due to low yield strength and local plastic deformation of their high coefficients of thermal expansion metal layer as well as delamination at the interface of the two materials caused by substantial thermal shear stress. Lim et al. [7] reported the detailed modeling and analyses of the two types of piston-like out-of-plane motion micromechanical structures which were also based on bimorph structures: a single bimorph and a flip-over bimaterial structure. Their results showed that the deflection predictions of the analytical model are in good agreement with those of the finite element model. In addition, the analyses of a micro-opto-mechanical sensor using interconnected flip-over bimaterial microstructures indicated that the analytical and finite element predictions agree with the experimental results within about 25%. Kim et al. [8] developed a single stepped beam structure for realizing out-of-plane motion. The height difference from the step features in the beam generates a bending moment from the thermal expansion. Its structure is quite simple for micro-scale fabrication. Ali et al. [9] investigated an out-of-plane electrothermal microactuators based on a single stepped beam. Due to its asymmetric structure, the fabrication process may require more steps. Chen et al. [10] demonstrated a step-bridge structure to act as an out-of-plane electrothermal actuator. The moving direction of the actuator can be specified by the step structure. The maximum deflection of a typical actuator using p^{++} Si layer fabricated by bulk micromachining was about 13 µm as driven at 54 mW. McCarthy et al. [11] designed a long slender single stepped beam which can buckle under thermal loading. The electroplated nickel beam with slight eccentricities offers an out-of-plane motion. The relation between deflection and temperature obtained by a closed form model is highly nonlinear. The predicted results were in good agreement with experimental measurements.

In general, accurate analyses of microactuators are a critical step in the design and fabrication of micro devices due to the complexity of the micro fabrication technology. For a long time, the finite element method has been successfully used to predict microstructure behaviors. In this study, we focus on designing a double stepped beam structure that is developed in order to produce larger out-of-plane motion for microvalve applications. The double stepped beam structure acts like three compliant hinges which provide a rotational degree of freedom to increase the out-of-plane displacement output. The behavior of the device is investigated by an electro-thermo-mechanical analyses with a finite element model. The performance of the device is also compared with the single stepped beam microstructure which was designed and published in the literature.

2. Design and analysis

2.1. Operational principle

Figure 1(a) is a schematic of double stepped beam for large out-of-plane motion. A Cartesian coordinate system is also shown in the figure. The structure is similar to two rigid links connected by flexible hinges. Both ends of the beam are fixed. As shown in Figure 1(b), upon the application of an input current through the beam, the beam is loaded by axial compressive force at each end due to thermal expansion. As a result of bending moment induced by the compressive force, the beam structure experiences an out-of-plane deflection. When the current is relieved, the beam retracts to its original shape as depicted in Figure 1(c). The different values of the out-of-plane deflection can be obtained by controlling the input current. The electrothermal actuator is planned to use for activating the microvalve to control the flow rate as depicted in Figure 2. As seen in this figure, without a current applied to the electrothermal actuator, the microvalve is completely opened. As a current passing through the actuator, the microvalve starts closing and thereby the flow rate of fluid is controlled by adjusting the input current.

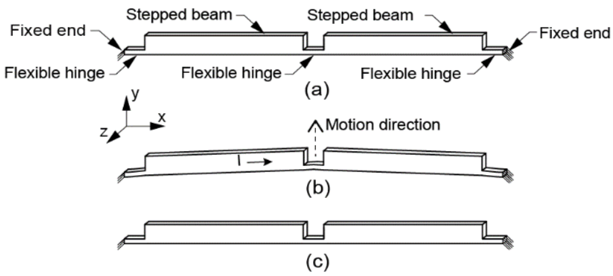

Figure 1. *Operational principle the double stepped beam microactuator*

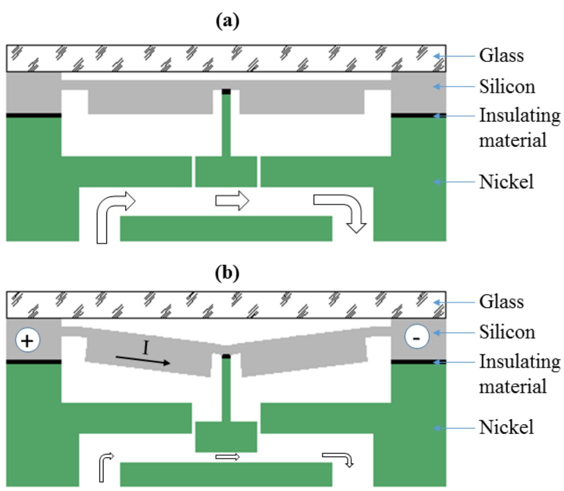

Figure 2. *Schematic cross-section of the electrothermal microactuator application for microvalve*

2.2. Design and modelling

Figure 3 presents the dimensions of the double stepped beam structure. It is designed to meet the standard of Taiwan Semiconductor Manufacturing Company (TSMC). In order to analyze the deformation of the beam under current loading, three-dimensional finite element analyses are employed by using the commercial ABAQUS software. The electro-thermo-mechanical analysis is carried out in two steps, electrical-thermal step and thermal-mechanical step. The initial temperature of the whole device is assumed at 25°C in the electrical-thermal step. It is known that heat conduction is dominant over free convection, while radiation is negligible at the microscale [12]. Therefore, in this investigation, the convection and radiation effects are ignored in the electrical-thermal step due to the small surface area. A gap of 1 µm between the beam and substrate is also assumed to consider the heat conduction between the beam and the substrate. The cross-sectional view that illustrates the heat transfer path of the beam structure is shown in Figure 4. A three-dimensional model using the element type of DC3D8E is employed in the coupled electrical-thermal analysis to get the temperature distribution along the beam. Both ends of the beam are assumed to be linked directly to a heat sink which is at room temperature (25°C).

In the second step, thermal-mechanical analysis with three-dimensional model is performed. The ends of the beam are mechanically fixed while all other boundaries are kept free to move. The element, C3D8R, is used for this step. The temperature rise is taken from the results of the first step. The deformation and respective stress induced are obtained from this step. Silicon is selected as the material of the beam. The material is assumed to be linear elastic. Its properties used for simulation are listed in Table 1.

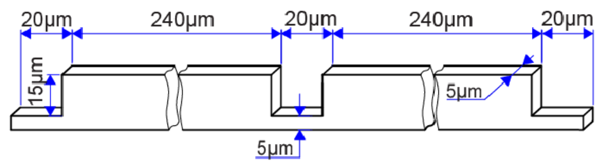

Figure 3. *Dimensions of the double stepped beam*

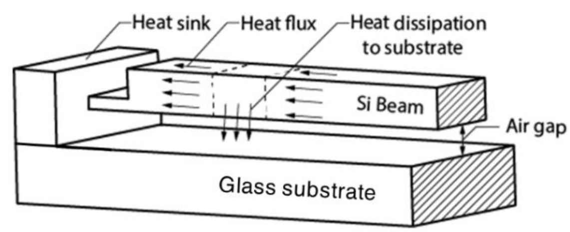

Figure 4. *The heat transfer path of the beam*

Table 1. *Material properties used in this simulation*

Material properties	Value
Density of silicon ($kg.m^{-3}$)	2330
Young's Modulus of silicon (GPa)	130
Poision's ratio of silicon	0.28
Thermal conductivity of air ($W/\mu m.^{o}C$)	0.026×10^{-6}

Since the electrothermal microactuator is designed to work under a wide range of temperature rise for microvalve applications, the resistivity, thermal expansion coefficient, and thermal conductivity of the selected silicon are temperature dependent during simulation processes. The resistivity of the material is assumed as follows [6; 13; 14]:

$$\rho = (2\times10^{-3})\times[1+(1.25\times10^{-3})\times(T-300)] \quad (1)$$

where the temperature is in Kelvin and the resistivity is in Ωcm.

The thermal conductivity of the material is given as [8]:

$$\kappa = (5\times10^{-4})\times T^2 - 0.4706\times T + 164.15 \quad (2)$$

where the temperature is in degrees Celsius and the thermal conductivity is in W/m/°C. The coefficient of thermal expansion is [8]:

$$\alpha = (3\times10^{-9})\times T + 3\times10^{-6} \quad (3)$$

where the temperature is in degrees Celsius.

Figure 5(a) shows a mesh for a finite element model. The finite element model has 63008-node elements. A mesh convergence study is initially performed to obtain accurate solutions of deflection and induced stress. A close-up view of the mesh near the fixed end of the beam is also shown in the figure. For all analysis, the mesh sizes are 0.5 µm and 1.0 µm for flexible hinges and stepped beams, respectively. Figure 5(b) shows a deformed mesh when a current is applied to the ends of the beam.

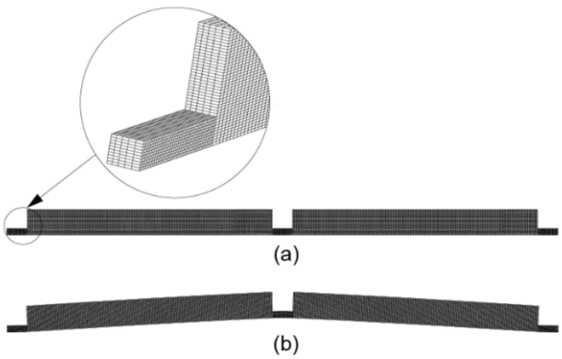

Figure 5. *Undeformed mesh (a) and deformed mesh (b) of the finite element model*

3. Results and discussion

Figure 6 shows the temperature distribution along the beam at an input current of 15 mA. Due to the assumption of heat sink attached to both ends, the temperature rise is symmetric with respect to the middle plane and the highest temperature is obtained at the middle plane of the beam. It is also noted that the heat conduction from the beam to the substrate through an air layer (1 µm thickness) is not fast enough to cause the temperature difference in the y-direction owing to the low thermal conductivity of air. The Mises stress in the beam caused by thermal expansion at the same applied current are also shown in Figure 7. The largest stress, 1.46 GPa, is much smaller than the yield strength of the typical silicon material (7GPa) [3], indicating that the beam structure is in an appropriate design.

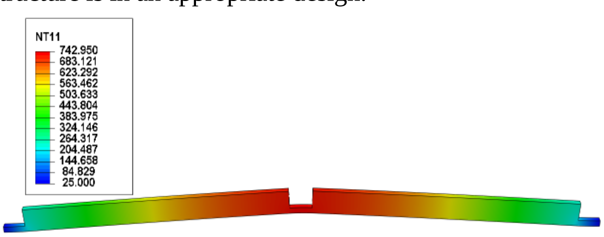

Figure 6. *Temperature distribution (^0C) in the beam under an applied current of 15 mA*

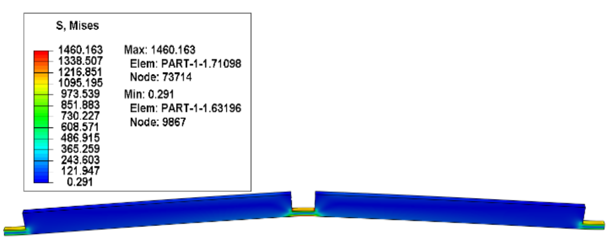

Figure 7. *Mises stress (MPa) induced in the beam under an applied current of 15 mA*

Figure 8 shows steady-state temperature distributions along the beam under different currents passing through obtained from the electrical-thermal simulation. The temperature rise is symmetric and proportional to the input current. The temperature profile is similar to parabolic curve. The closer to the ends the location is, the lower temperature is observed. This is due to heat conduction to the heat sink at the beam ends. As seen in this figure, the highest temperature is around 99°C at a current of 8 mA and it rises to nearly 743°C for the case of 15 mA. The highest temperature rise attained at the middle surface of the beam under various applied currents is also presented in Figure 9. The nonlinear relationship between the highest temperature and the input current observed is mainly due to the temperature dependence of the electrical resistivity and thermal conductivity of the material.

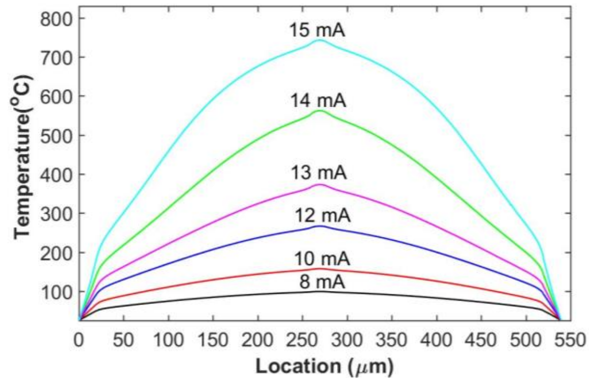

Figure 8. *Steady state temperature distributions along the beam under different currents passing through*

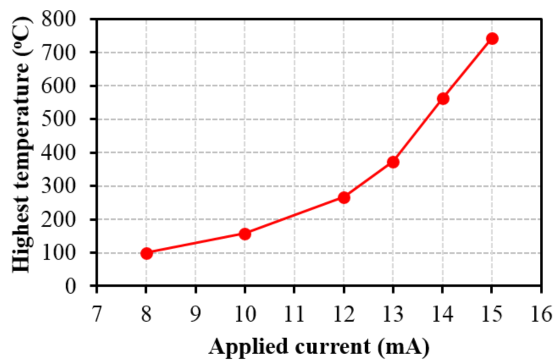

Figure 9. *Highest temperature rises versus applied currents*

Figure 10 displays the deflection contour of the double stepped beam and single beam at an input current of 15 mA obtained from the thermal-mechanical analysis. It can be seen from this figure that the double stepped beam produces a much larger maximum deflection than single beam does. The deflection at the center of the double stepped beam corresponding to the input current is plotted in Figure 11. The maximum deflection increases gradually with the input current from 8 to 11 mA. However, this increase becomes significant at higher input currents ranging from 11 to 15 mA. The maximum deflection of a single stepped beam as a function of the input current is also shown in Figure 11. In comparison, it is obvious that the proposed double stepped beam structure has a much larger out-of-plane for the current ranging from 11 to 15 mA. In particular, the maximum deflection of the double stepped beam structure is about 4.9, 6.6, and 6.8 times greater than that of the single stepped beam structure with the input currents of 13, 14, and 15 mA, respectively. This is because, at high input current, the longitudinal expansion due to the temperature rise is large enough to make the beam experience a clear bending mode. The results show that the deflection behavior of the beam is nonlinear with respect to the temperature variation. This is because that the electrothermal actuator designed based on a double stepped beam structure will behave similarly like an eccentric beam when subjected to an axial compression load. It means that the beam will buckle at a certain temperature, so-called critical temperature. In other words, the deflection and stress induced by thermal expansion increase in a discontinuous manner. Based on the Euler buckling theory which is the deflection and axial compression force generated by thermal expansion for a buckling beam governed by a nonlinear partial differential equation, the relation between the deflection and temperature rise for a thermal buckling beam have been proved to be nonlinear [11; 15]. Besides, the increase of the deflection is proportional to the applied current, revealing that the beam deflection can be controlled by the input current. Accordingly, the flow rate of the microvalve activated by the electrothermal microactuator can be gradually adjusted.

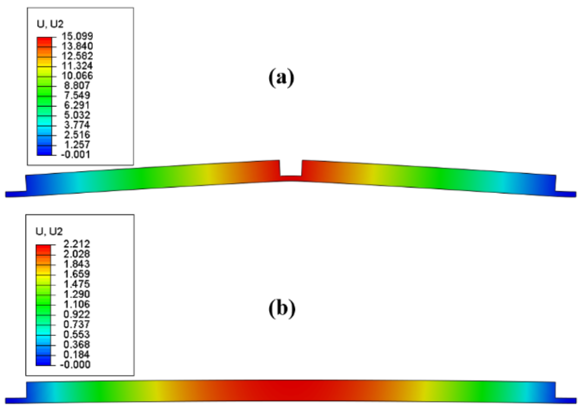

Figure 10. *Deflection contour at an applied current of 15 mA: (a) double stepped beam and (b) single stepped beam*

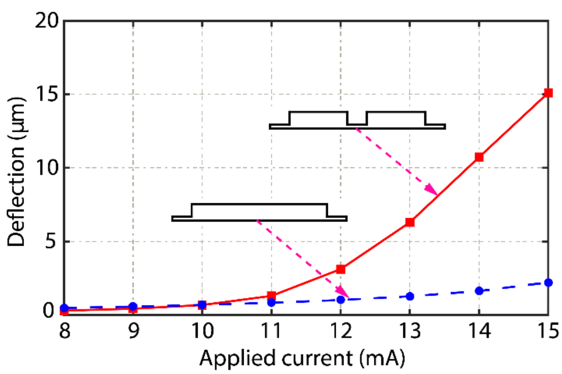

Figure 11. *Maximum deflection as a function of the applied current*

4. Conclusion

A new double stepped beam structure for large out-of-plane motion is proposed and analyzed. Its excellent performance is validated by finite element method. The maximum deflection of the beam structure reaches 15.1 μm under an input current of 15 mA, while the temperature rise is around 740ºC. The maximum out-of-plane deflection of the beam structure is 6.8 times higher than that of a single stepped beam structure at 15 mA. Furthermore, the Mises stress value is still far less than the yield strength of the typical silicon material base on the finite element analyses, confirming that the beam structure will work well under assumed conditions. In the next step, the microactuator device will be fabricated for further experimental validation.

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