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Vertically driven microactuators by electrothermal buckling effects

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Abstract

Vertically driven microactuators based on electrothermal buckling effects have been demonstrated. These microactuators are fabricated by a modified surface micromachining process that uses undoped polysilicon as the structural material. The core component of the microactuator is a rectangular plate ($300\times300\times2$ μm^3) which is suspended 2 μm above the silicon substrate and is supported by two anchor legs. The plate is actuated by a resistive heater that runs across the microactuator and is defined by a phosphorus drive-in step. Theoretical models, including electrothermal and thermoelastic behavior of microstructures, have been established and simulated. It has been experimentally demonstrated that these microactuators are capable of creating a maximum vertical actuation of 50 μm. Furthermore, a tiny cylindrical copper block, 330 μm in diameter and 760 μm in length, has been successfully lifted. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Microactuator; Vertical drive; Electrothermal buckling; Buckling

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1. Introduction

Microactuators are of interest for a variety of applications in the emerging field of microelectromechanical systems (MEMS). One of the very early demonstrations of microactuation dates back to the 1960s when metal microresonators were used in resonant gate transistors as a 'gate' structure [2]. Research in microactuators has grown rapidly and several important milestones have been demonstrated, including the successful operations of micro-mirrors [3], electrostatic micro-motors [4], magnetic micro-motors [5] and electrostatic comb resonators [6]. Recent developments in microactuator research have emphasized high output power and high actuation force that are capable of physically moving micro objects for micro-assembly [7] or micro-positioning [8].

In the design of microactuators, several driving mechanisms have been widely adopted such as electrostatic [3,4,6], magnetic [5,9] and electrothermal forces [10–12]. Among these actuation mechanisms, electrothermal actuation is very attractive because it can be easily generated with a moderate input power. On the other hand, lateral [6,10], rotational [4–6] or combined vertical/rotational motions [3,7,8, 11,12] of microactuators have all been demonstrated. However, the capability of lifting up a platform purely without rotational motion is rather difficult since most microactuators have to rotate around a fixed anchor on the substrate. This paper presents the design, analysis and testing issues of a new class of microactuators that are capable of lifting up a micro platform with relatively small rotational angles. Electrothermal buckling effects provide the driving force and the possibility to move vertically with minimum rotations.

2. Design and fabrication

2.1. Design

Fig. 1 shows the schematic diagram of the microactuator that is composed of an actuator plate, two anchor legs, a resistive heater and two contact pads. The actuator plate has a square shape with an area of 300×300 μm^2 that can be

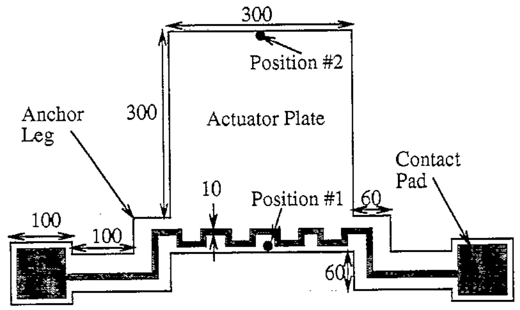

Fig. 1. The schematic diagram of a microactuator based on electrothermal buckling effects.

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utilized as the holder for micro objects to be actuated. Two anchor legs with a width of 60 μm are used to support the actuator plate. The meander shape of these legs helps to increase the flexibility for vertical deflection under the buckling condition and to minimize the rotational motion. The resistor has the meander shape on top of the actuator plate to provide uniform and prompt heating. Electrical power is supplied via the contact pads and the two supporting anchor legs.

2.2. Fabrication

A modified surface micromachining process is used to fabricate these microactuators. The fabrication process begins with clean prime silicon wafers. A 0.15 μm thick layer of LPCVD (low pressure chemical vapor deposition) silicon nitride is deposited as the thermal and electrical insulation layer. It is followed by a thick, 2.1 μm LPCVD silicon oxide deposition as the sacrificial layer. Anchors are then defined by using the first mask and wet HF etching. After these steps, Fig. 2a applies. Polysilicon [1] is deposited as the structural layer with a thickness of about 2.2 μm. The wafer is then put into a high temperature thermal oxidation process to grow about 0.5 μm thick thermal oxide on the top surface of polysilicon. This process not only provides thermal oxide as the masking layer for the phosphorus doping process but also anneals the polysilicon layer to relieve the residual stress. Fig. 2b shows the cross-sectional view of the wafer. The second mask is used to define the heating resistors. Wet HF is applied for the definition of the oxide mask. After removing the photoresist, the wafer is cleaned and put into a high temperature furnace for phosphorus pre-deposition by flowing $POCl_3$ at 1000°C for about 40 min. A drive-in process is continued at 1050°C for about 50 min. Fig. 2c shows the completion of these steps. The measured average sheet resistance is about 170 Ω/square. The third mask is then used to pattern the microactuators. Two wet etching processes are followed. First, HF solution is used to define the top oxide masking layer. Second, the silicon etchant of HNO_3:H_2O:NH_4F = 64:33:2 is used to etch polysilicon to define the microactuators. Finally, the sacrificial oxide layer and the top oxide masking layer are removed by concentrated HF and microresonators are released and dried. Fig. 2d shows the completion of the fabrication process. Fig. 3 is the SEM image of a fabricated microactuator. Heating resistors can be identified by their dull white color.

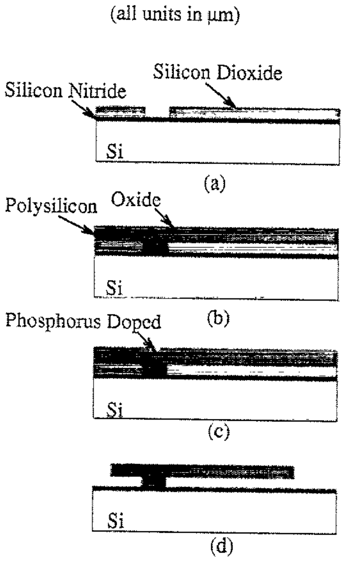

Fig. 2. The fabrication sequence.

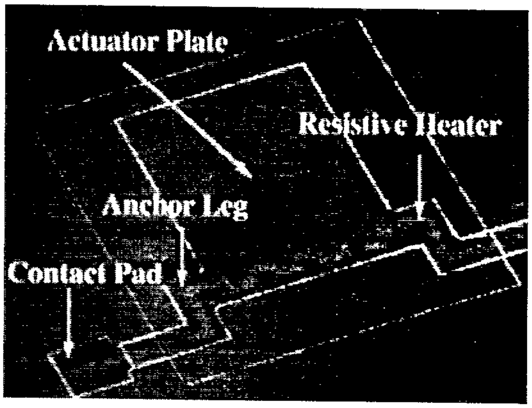

Fig. 3. A SEM image showing a fabricated microactuator.

3. Theoretical analysis and numerical simulation

3.1. Theoretical analysis

Previously, Lin et al. [13] have developed a theoretical model for straight clamped–clamped micro beams under electrothermal buckling conditions. Fig. 4 shows the schematic diagram of such a buckled micro beam. The maximum deflection at the center of the beam is a function of temperature:

$$y_{\max}=4\beta\sqrt{\frac{I}{[\alpha\Delta T-\varepsilon]A}} \tag{1}$$

where A and I represent the cross-sectional area and moment of inertia of the beam. T is the average temperature and ε the strain of the beam. α and E are the thermal expansion coefficient and Young's modulus of polysilicon. β is a function of the maximum deflection angle, $\theta_{\max}$, which occurs at one-fourth of the beam length as shown in Fig. 4.

$$\beta=\sin\frac{\theta_{\max}}{2} \tag{2}$$

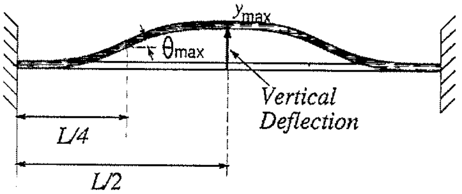

Fig. 4. The schematic diagram of a straight, clamped–clamped beam after buckling.

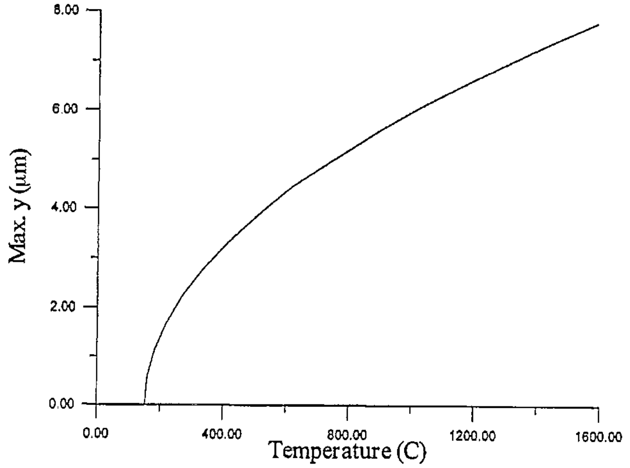

Fig. 5. Theoretical maximum deflections with respect to temperature differences.

Temperature differences as well as the strain and length of the total beam length can be derived in terms of thermal loading, P, and other parameters [13]:

$$\Delta T=\frac{4\mathrm{K}(\beta)EA\sqrt{PEI}-PLEA-P^2L}{PLEA\alpha} \tag{3}$$

$$\varepsilon=\frac{\Delta L}{L}=\frac{\mathrm{K}(\beta)}{2\mathrm{E}(\beta)-\mathrm{K}(\beta)}-1 \tag{4}$$

$$L=\frac{4[2\mathrm{E}(\beta)-\mathrm{K}(\beta)]}{\sqrt{\dfrac{P}{EI}}} \tag{5}$$

where K(β) and E(β) are the complete elliptic integrals of the first kind and second kind. To solve these equations with known geometry and properties, maximum deflection angles are first given from 0 to a small number. The corresponding values of strain are calculated in Eq. (4) and loading forces are calculated by Eq. (5). Eq. (3) is then used to solve temperature differences. Finally, maximum deflections are calculated by Eq. (1).

The microactuator as designed in this paper (see Fig. 1) has a rather more complicated geometry than the simple, straight beam structure as derived above. If we assume that the actuator plate does not bend under buckling, the above theoretical derivation can provide preliminary approximations for microactuators presented in this paper. However, it is noted that this analytical solution underestimates the maximum deflection under buckling since the rigidity of the actuator plate is not infinity. Fig. 5 shows the theoretical prediction of maximum deflections vs. temperature differences. It is observed that a temperature difference of only 150°C can cause buckling and if the temperature is close to the melting temperature of polysilicon at about 1400°C, the actuator moves about 7 μm vertically.

3.2. Numerical simulation

3.2.1. Electrothermal simulation

Numerical simulations are applied to examine the electrothermal buckling effects. First, temperatures with respect to the energy generated by the input power are simulated. According to the experimental measurements, the maximum input voltage and current are close to 15 V and 50 mA. The heat generation per unit volume is calculated to be 1.5×10^{12} W/m^3 at this level. A three-dimensional electrothermal model that uses about 34 000 nodes and 32 000 elements has been established by using a finite element analysis software, ANSYS [14]. It is found that the microactuator body reaches a rather uniform and high temperature of about 1500°C under this input power that is consistent with experimental observations. This predicted value is expected to be higher than the real temperature, since this model did not consider the energy losses through the two metal probes.

3.2.2. Thermal buckling simulation

Two types of thermal buckling simulations have been implemented. One includes the residual stress effects and the other does not. First, a temperature rise of 1200°C is given in both cases. When the residual stress effect is neglected, the simulation result suggests a maximum vertical deflection of 22.4 μm at the bottom center of the plate (position #1 as shown in Fig. 1). According to the simulation result, the plate not only bends along the direction parallel to the direction of the resistor but also rotates slightly (1°) toward the far side (position #2 in Fig. 1). The simulation that includes the residual stress effects is based on experimental measurements on the initial shape of the actuator plate. It is found that the actuator plate has an initial vertical deflection of about 4.3 μm at the lower center (position #1 in Fig. 1) and an initial rotational angle of 1°. An initial force is applied to emulate this residual stress effect such that the shape of the actuator plate matches the experimental measurements. A temperature rise of 1200°C is then applied and Fig. 6 shows the simulation results. It is found that after the actuation, the maximum deflection is 36.6 μm and the rotational angle is 3.2°. Moreover, the actuator plate bends along the direction of two

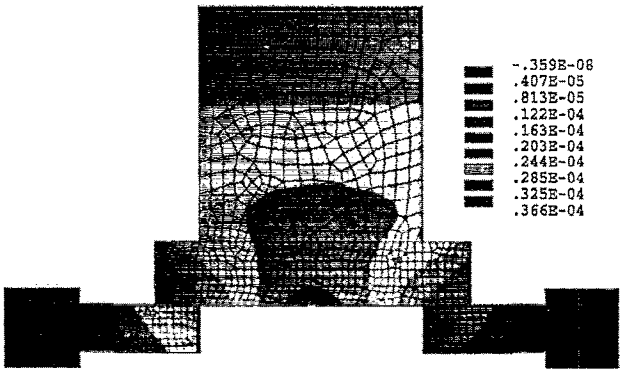

Fig. 6. ANSYS simulation results of vertical deflections after buckling (with the consideration of initial residual stress).

anchor legs and these legs also experience bending and rotational movements.

4. Experimental results and discussions

Experiments are conducted by using a probe station and observed under an optical microscope. It is observed that the dynamic responses of the microactuators follow the input frequency to about 100 Hz. The magnitude of vertical movement reduces as the input frequency increases. The thermal responses cannot catch up with the electrical inputs at high input frequency. Furthermore, if the input current is too high or microactuators are under a long period of actuation, permanent damage occurs and the microactuators cannot bounce back to their original positions. These effects are probably caused by permanent plastic deformation and thermal creep.

The input power is recorded and vertical deflections are measured by using the focus/defocus method which gives a measurement error of about ±1 μm. Ten individual tests have been conducted and the average values are plotted in Fig. 7. It is observed that when the input current is higher than 50 mA, the microactuator breaks due to high temperature melting effects. Vertical deflections at two positions are measured. Position #1 is at the bottom center and position #2 is at the top center of the actuator plate as shown in Fig. 1. Under an input current of close to 50 mA and an input voltage of 15 V, position #1 reaches a maximum vertical deflection of 50 μm. Position #2 moves about 36 mm vertically, which indicates about 3.2° rotational movement.

These experimental results are compared with both the analytical analysis and numerical simulations. It is found that the simplified theory predicts far less vertical deflection than the experimental observations. Obviously, a more detailed theoretical modeling that considers the complicated geometrical and residual stress effects of the microactuator can be performed to achieve better estimations. The finite element analysis which includes the residual stress effect seems to give a reasonable prediction for both maximum deflections and rotational angles. More accurate simulations can be accomplished by including the step-up boundary condition at the anchors [15], which is a typical fabrication feature of the surface micromachining process. Furthermore, this step-up condition seems to cause microactuators to move up instead of moving down under the buckling condition.

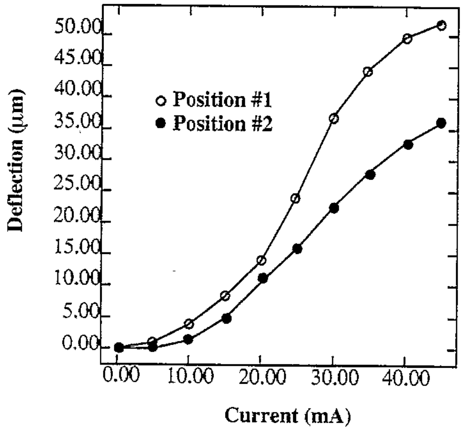

Fig. 7. Experimental results of maximum vertical deflections vs. input currents.

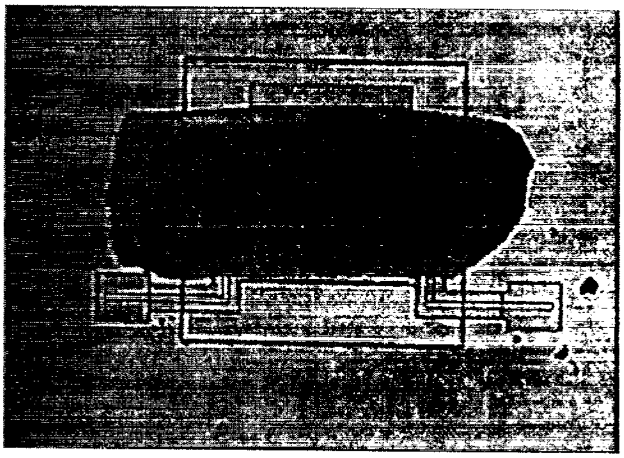

Fig. 8. A photomicrograph showing the microactuator lifting a copper block.

These microactuators have been tested to push micromechanical components. In the first test, a small amount of clay has been put on the actuator plate. After passing electrical power, the clay is melted and fixed on the actuator plate. Copper wires that have high melting temperature are then tested. Several pieces of copper blocks have been successfully lifted by these microactuators. The largest one has a diameter of 330 μm and a length of 760 μm as shown in Fig. 8. When an input voltage of 9 V is applied, the copper block is lifted. It is calculated that this copper block is about 1000 times heavier than the body of the polysilicon microactuator.

5. Conclusions

We have successfully demonstrated vertically driven microactuators by using electrothermal buckling actuation. These microstructures are fabricated by a modified surface micromachining process with a single polysilicon layer as the structural body. With less than 15 V, a vertical deflection of 50 μm has been be achieved. These microactuators have attractive features and unique combinations of low input voltage, single layer structure, electrothermally driven, and high vertical deflection. A simplified electrothermal buckling model has been developed to provide preliminary estimations of microactuation. Moreover, a three-dimensional finite element model has been established to give better understanding of the electrothermal buckling effects and the simulation results are consistent with experimental observations. Further investigations on theoretical analysis, simulation and experiments are expected to build better designs and analytical models for these electrothermal microactuators.

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Biographies

Liwei Lin received MS and PhD degrees in Mechanical Engineering from the University of California, Berkeley, in 1991 and 1993, respectively. He was a research assistant at Berkeley Sensor & Actuator Center, an NSF/Industry/University research cooperative center, during his graduate study. He joined BEI Electronics USA from 1993 to 1994 in research and development of microsensors. From 1994 to 1996, he was an Associate Professor in the Institute of Applied Mechanics, National Taiwan University, Taiwan. Since 1996, he has been an Assistant Professor at the Mechanical Engineering and Applied Mechanics Department at the University of Michigan. His research interests are in microelectromechanical systems (MEMS) including design, modeling and fabrication of microstructures, microsensors and microactuators. Dr. Lin holds 4 US patents in the area of MEMS.

Shiao-Hong Lin received his BS degree in agricultural mechanical engineering from National Taiwan University in 1995 and MS degree from the Institute of Applied Mechanics, National Taiwan University, in 1997. He is currently serving a two-year obligatory military service in Taiwan. His research interests are in microelectromechanical systems including design, modeling and fabrication of microstructures.