Microfabricated Tweezers with a Large Gripping Force and a Large Range of Motion

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Abstract

A new microtweezers design is presented based on bimetallic actuation and silicon bulk micromachining. The two arms of the tweezers are 2000μm long and 100μm wide p^+ silicon cantilevers, each several microns thick. Bimetallic actuation using gold is integrated on one arm while the other arm is passive. The metal/p^+ silicon thicknesses of the actuation arm are 7800Å/5μm. A 30mW input power deflects the actuation arm by 200μm at the tip, fully closing the tweezers. At 30mW input power, the gripping force of the actuation arm is estimated near 11μN for a 200μm-sized object.

1 Introduction

Of the different thermal microactuation techniques reported, including bimetallic, thermopneumatic, and shape memory alloy, the bimetallic effect is well suited for microfabrication. Although several papers have been published on bimetallic actuation [1]–[3], basic information on the thermo-mechanical characteristics of bimetallic actuators is sparse. The primary objective of this paper is to further investigate bimetallic microactuation through a study of microfabricated bimetallic cantilever microactuators. As a vehicle for the basic studies here, we have developed and used a device (i.e., microtweezers) that utilizes bimetallic cantilever microactuators to address micromanipulation needs.

2 Microtweezers Design and Fabrication

A new design for microtweezers is presented in this paper and is shown schematically in Fig. 1. A brief discussion of the microtweezers design and fabrication is provided here. For details, the reader is referred to [4]. The microtweezers design utilizes two cantilevered gripping arms each 2000μm long and 100μm wide connected to a silicon support piece as shown in Fig. 1. The two cantilevers function as the two arms of the tweezers to clamp and release the object to be manipulated.

Heavily-boron-doped (p^+) silicon is used as the primary structural material for the two cantilevers. The silicon support, which has a 3×3mm^2 area and is 275μm thick, serves as the mechanical support handle of the microtweezers (Fig. 1). The two cantilevers are aligned along the <100> direction, and the edges of the square silicon support are aligned along the <110> direction. A 0.45μm silicon dioxide layer is thermally grown on the top surface of the top p^+ silicon cantilever arm for electrical isolation. A 7600Å/200Å gold/chromium film is sputtered and patterned on top of the upper arm in order to provide for bimetallic actuation of that arm. The wafer is annealed in N_2 at 450°C for 20 minutes to obtain good adhesion between the gold/chromium film and silicon dioxide, as well as to stablize the mechanical and electrical properties of the gold [4]. The total width of the patterned gold film is 55μm, covering about half of the surface of the top cantilever. This sputtered gold film is also used to provide the heating resistor (Fig. 1). The tweezers structure is etched in EDP as a final step to remove the silicon between the two arms and complete the device fabrication.

The top arm of the microtweezers incorporating the bimetallic actuation is hereafter referred as the 'actuation arm'. Electric power input into the metallic strip by resistive heating will raise the temperature of the gold/p^+ silicon bimetallic actuation arm. Because of the thermal expansion coefficient difference between p^+ silicon and gold, the actuation arm will deform toward the lower p^+ silicon cantilever. This accomplishes the gripping function of the microtweezers. When electric power is removed, the temperature of the actuation arm decreases back to room temperature and the microtweezers open.

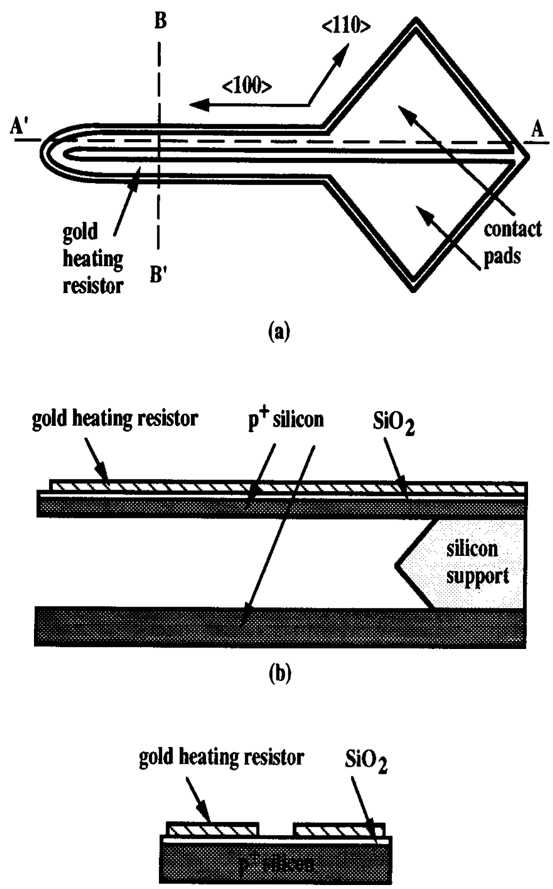

Figure 1: Schematic diagrams showing the new microtweezers design (not to scale): (a) top view; (b) cross-sectional view along line A-A'; (c) cross-sectional view along line B-B'.

In order to simplify the fabrication, only the top cantilever of the microtweezers has the metallic heating element on it. The bottom cantilever (hereafter referred to as the passive arm) is made thicker to stiffen that arm against bending during the gripping action. However, the actuation mechanism can also be applied to the bottom cantilever, in which case both arms would be actuated for the gripping action. With both arms active, a smaller temperature increase would be required to close the tweezers since each arm would only have to bend half of the initial separation distance at the tip.

The proposed microtweezers design has some advantages over previous designs [5, 6]. Bimetallic microactuation provides significantly larger gripping forces than electrostatic microactuation. The bimetallic design has a wide gripping range (e.g., over two hundred micrometers). Finally, the design presented can be integrated with strain sensors to provide direct force feedback. One major drawback of the bimetallic microtweezers is that the temperature of the microtweezers may be much higher than room temperature when gripping objects. Based on our current design, the temperature may be as high as 170°C at tweezers tip for complete closure. However, it is possible to redesign the device such that the heating resistor is well away from the grasping region.

The actuation arm of the microtweezers is made of p^+ silicon, silicon dioxide, and gold. Therefore, the shape (or curvature) of the actuation arm upon fabrication depends not only on the internal residual stress distribution in p^+ silicon but also on the stresses inside the gold film and the silicon dioxide layer. The overall bending moment generated by p^+ silicon, silicon dioxide, and gold determines the final shape of the actuation arm of the microtweezers. Our goal has been to develop a fabrication process to produce bimetallic microtweezers with a desired actuation arm curvature. The tweezers initial (i.e., power off) opening is determined by the actuation arm curvature and the wafer thickness (i.e., 275μm for our wafers), assuming the passive arm to be flat.

Figure 2 shows a scanning electron microscope photo of two fabricated microtweezers. The picture has been taken with the actuation arms of the two microtweezers in the lower position with respect to the passive arms. The thick (i.e., 13.5μm) p^+ passive arms are flat as can be seen in the figure. The bending moment generated as a result of residual stresses inside the actuation arm constituent films causes an initial curvature of this arm. The actuation arm is made thin (i.e., near 5μm thick for the p^+ portion) and therefore compliant to enhance its actuated motion. As a result, its curvature is sensitive to the residual stress induced bending moments.

The upper tweezers in Fig. 2 is typical of the actuation arm curvature and tweezers initial opening (which is near 200μm) which result from the baseline fabrication process. As will be seen later, tweezers with 200μm openings can be closed fully with an input power of about 30mW and display a linear opening/input power behavior. The variation in the tweezers' openings as a result of process variation on a wafer or from wafer to wafer are discussed in [4].

It is possible to vary the tweezers initial opening over a wide range by manipulating the p^+ diffusion and the subsequent thermal oxidation process steps. The lower tweezers in Fig. 2 demonstrates this capability. Note that the required input power, as well as the maximum temperature of the tweezers actuation arm, for closing the tweezers on an object is affected by the initial opening size of the tweezers. Correspondingly, for small objects, a small initial opening may be more desirable.

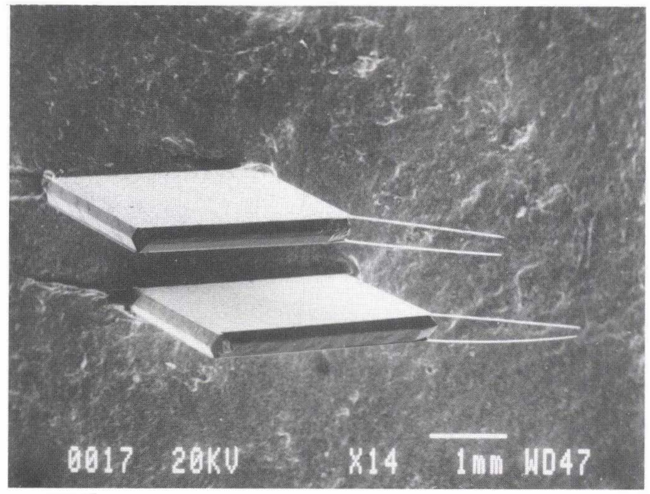

Figure 2: A SEM photo showing two microfabricated tweezers. The upper tweezers is from a typical wafer resulting from our baseline process. The lower tweezers demonstrate the capability of adjusting the microtweezers initial opening.

3 Thermal Characterization

The temperature profile of the actuation arm of the microtweezers is measured using a thermocouple direct contact and an infrared scanning microscope method. The data is then compared with finite element thermal analysis results from [4]. For the direct thermocouple contact method, a tiny E-type (Chromel-Constantant) thermocouple [7] with a 10μm wire diameter and a 25μm radius tip mounted on a three-axis micropositioner has been used. The micropositioner has an accuracy of 1μm about each of the three axes. The thermocouple thus can be positioned to measure the surface temperature along any axis by direct contact with the surface of device. 'TC Method' is used hereafter to indicate temperature measurements using a thermocouple.

Due to the small dimensions of the microtweezers, ordinary precision infrared pyrometers cannot be used to measure the surface temperature of the microtweezers because of the relatively large spot size (or measuring area of ordinary pyrometers). Considering the microtweezers small dimensions, CompuTherm III [8] is capable of measuring the surface temperature of the microtweezers with sufficient spatial resolution (i.e., 15μm). This instrument is an infrared scanning microscope. It uses an indium antimonide (liquid N_2 cooled) infrared detector to detect the emitted IR energy in the 3 to 5μm spectral range. 'IR method' is used hereafter to indicate the temperature measurements using the CompuTherm III system.

The surface temperature along the length (e.g., X-axis) of the actuation arm was measured using both TC and IR methods at different input power levels. In all temperature measurement experiments, a constant voltage source was used to supply power to the actuation arm and the current was monitored by an ammeter. The applied voltage was adjusted to obtain a desired input power with an accuracy of $\pm$0.5 mW.

Figure 3 shows the measured temperature profiles for the bimetallic actuation arm using TC and IR methods at input powers of 18 and 20mW, respectively. Reliable data from the infrared scanning microscope measurement ends at around X=1000μm for reasons described in [4]. An can be seen from Fig. 3, both experimental methods indicate the same temperature decrease toward the mechanical support. The difference between these two measurements for the maximum temperature is less than 10%, which is within the input power difference for the two measurements. Clearly, the silicon support acts as a heat sink, reducing the temperature toward the support end. Therefore, a constant temperature profile along the length for a bimetallic cantilever as has been assume in previous work [1]–[3] is not accurate.

The fit to the temperature data using finite element analysis described in [4] is also shown in Fig. 3 for a 20mW input power. This temperature distribution is in good agreement with the experimental results, assuming a heat transfer coefficient (h_{tc}) of 480W/m^{2}K.

A point of concern in our temperature measurements using the TC method is the extent to which the thermocouple modifies the temperature distribution around the cantilever, in particular in the tip region. We have noted that the temperature data from the TC method consistently show a drop near the tip region (see Fig. 3) which is not predicted by the finite element model when a good fit is obtained toward the support end (see Fig. 3). The heat loss due to conduction through the thermocouple is thought to be responsible for this effect. A model was constructed to study (using finite element thermal analysis) the temperature change in the actuation arm due to the introduction of the thermocouple. Preliminary results from the model confirm that the presence of the thermocouple near the tip of the actuation arm results in a decrease (by as much as 20%) in the temperature of that region.

4 Power/Deflection Relation

As described earlier, the microtweezers typically have an initial opening near 200μm. An input power near 30mW has typically been needed to just close the microtweezers. This input power corresponds to a maximum actuation arm temperature near 170°C.

The tip deflection of the actuation arm at different input powers was measured [4]. Figure 4 shows the measured tip deflection of the actuation arm under different input powers. For this measurement, the passive tweezers arm was broken off so that the actuation arm could be deflected beyond 200μm. The fit of a thermo-mechanical model derived in [4] to the data is also shown in Fig. 4. Finite element thermal analysis is used to determine the cantilever temperature profile for each input power. A constant h_{tc} of 480W/m^{2}K is used for the thermal analysis based on the results from the temperature measurements above. The temperature data at a given input power is then used to calculate the cantilever deflection by integrating the curvature equation derived in [9] along the cantilever length.

As seen from the experimental data, the tip deflection of the actuation arm increases linearly with input power up to around 40mW, at which point the slope of the tip deflection versus input power decreases. This general behavior is also found in the work from others [1]. The experimental tip deflection results deviate from the model also for input powers larger than 40mW. There could be two explanations for the discrepancy between the model and the experimental results at larger input powers. First, a constant heat transfer coefficient (h_{tc}=480W/m^{2}K) is no longer valid in this regime. Therefore, the calculated temperature distribution is overestimated by using a lower h_{tc} value and results in a higher tip deflection.

A second explanation is the re-annealing of the actuation arm at higher operating temperatures (higher input powers). The bimetallic actuation arm fabricated in our microtweezers is annealed in N_2 at 450°C for 20 minutes for good adhesion between the gold and p^+ silicon, as well as to stablize the electrical and mechanical properties of the gold [4]. The resistivity of the gold film would decrease with further annealing. As a result, the resistance of the heating resistor would decrease, leading to increased heat generation in parasitic series resistances and reduced heat generation in the heating resistor.

For input powers below 40mW, the tip position and the curvature of the actuation arm recover their original power-off values as the input power is removed after each cycle of operation. However, at high input powers ($\geq$40mW), the tip position and the curvature of the actuation arm do not return to their original power-off values when the input power is removed. For example, the power-off tweezers opening increases by nearly 20μm from its original value (e.g., 200μm) after it has been operated with an input power of 52mW. The maximum temperature of the actuation arm is near 220°C for an input power of 40mW. It seems that at temperatures above 220°C further annealing of the gold takes place. In addition to affecting its electrical properties, this annealing also leads to a change in the mechanical properties (e.g., residual stress) of the film, affecting the power-off tip position and curvature of the actuation arm.

Therefore, for reliable operation of the microtweezers, the maximum temperature of the actuation arm must be kept well under the annealing temperature. This condition is satisfied since an input power of 30mW is sufficient to fully close the microtweezers. In this regime of operation, the relationship between the microtweezers tip opening and input power is linear; the slope of the model tip deflection versus input power is 6.7μm/mW. This is in good agreement with the experimental data which is 6.9μm/mW. Thus, for the low input power regime, the thermo-mechanical models are effective tools for predicting the tip deflection of the actuation arm. The equivalent force [4] is estimated at 15μN for an input power of 40mW, which corresponds to 3.7×10^{-4}N/W in the linear characteristic region.

5 Response Time

Although the response speed is not critical for the operation of the microtweezers, it is still helpful to know the response time of the bimetallic cantilever actuator. A high speed video camera system (SP2000 [10]) is used to record and analyze the motion of the actuation arm. Figure 5 shows the step response of the tip deflection of the actuation arm during heating and cooling cycles, respectively. Although the recording speed in the measurement is 1000 frame per second, the relatively small changes in the tip deflection lead to an error of $\pm$2msec in the time measurement. As can be seen from the data, the step response time for both cases is near 60msec; the heating and cooling times are nearly the same.

6 Manipulation of Objects

Successful demonstrations of the microtweezers operation have been made. In these demonstrations, the microtweezers were amounted on a micropositioner and used to manipulate objects under a microscope. An adjustable voltage source was used to control the opening and closure of the microtweezers to pick up or to release the objects. In one demonstration, small crystals of salt about 100μm in size were picked up, rotated (e.g., 360°), moved around, and repositioned. In a second demonstration, grabbing and moving of an optical fiber (also around 100μm) into a v-groove was demonstrated. Finally, the alignment of two optical fibers by using the microtweezers to grab and align one fiber to the other was demonstrated.

7 Conclusion

A microtweezers design utilizing bulk micromachining and bimetallic actuation has been presented, demonstrating the potential of using bimetallic actuation to obtain large forces and deflections. It was experimentally demonstrated that the temperature distribution along the length of a bimetallic cantilever may not be constant since the support can act as a heat sink. It was noted that the re-annealing of the metal in the bimetallic cantilever may take place during operation if the input power is sufficiently high.

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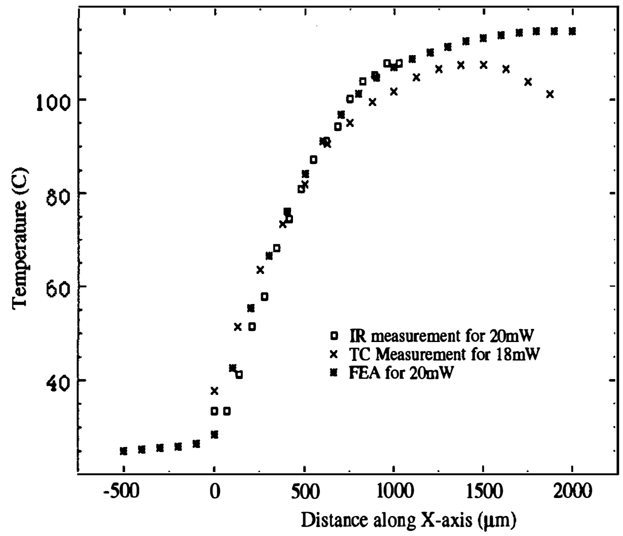

Figure 3: The temperature of the actuation arm of the microtweezers under 20mW input power. The X axis is along the length of the cantilever with X=0 at the support end and positive X toward the tip direction.

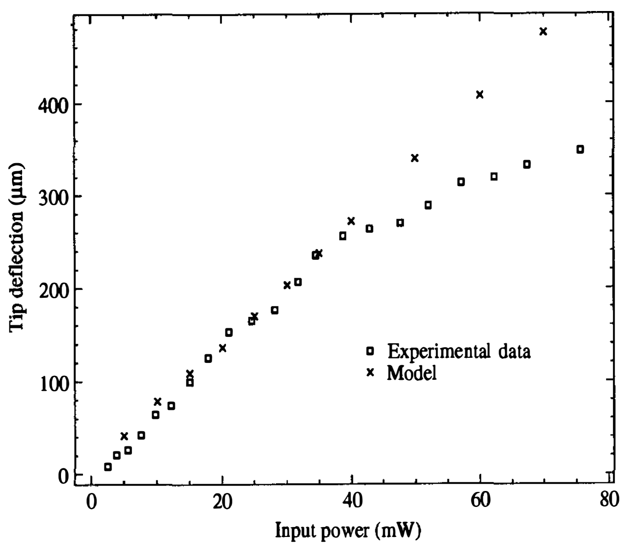

Figure 4: Experimentally measured and model tip deflections at the free end of the microtweezers actuation arm as a function of the input power.

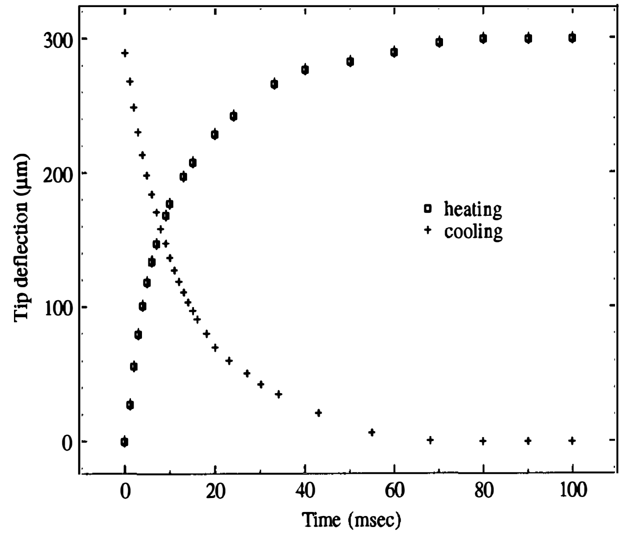

Figure 5: The step response of the tip deflection of the actuation arm during the heating and cooling cycles for an input power of 75mW.

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