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Feasibility Study of PDMS-based Thermal Microactuators

Dong-Weon Lee* and Jong-Sung Park[1]

MEMS and Nanotechnology Laboratory, School of Mechanical Systems Engineering,
Chonnam National University, Gwangju, Korea, 500-757
[1]MEMS and Nanotechnology Laboratory, Department of Mechanical Engineering,
Chonnam National University, Gwangju, Korea, 500-757

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In this paper, we describe the design, fabrication and characterization of new microactuators for a microelectromechanical system that requires a large displacement. The designed microactuators use the thermal expansion power of a transparent polymer, polydimethylsiloxane (PDMS), which has a high coefficient of thermal expansion. The locomotive mechanism of the microactuator is based on the motion of an inchworm. Various structures of the PDMS part are designed to find an optimal shape that provides the largest deformation for a given power. The structure of a microactuator with 1 mm length and 350 μm width is also optimized by numerical analysis using ANSYS. After the microfabrication of three different microactuators, several properties are evaluated by applying a thermal power generated from a heating source. The experimental results are in good agreement with the simulation results. One of the fabricated microactuators has a maximum displacement of about 725 μm.

1. Introduction

Endoscopy is a minimally invasive diagnostic medical procedure used to assess the interior surfaces of an organ by inserting a tube into the body. The instrument may have a rigid or flexible tube and can not only provide an image for visual inspection and photography, but also take biopsies and retrieve foreign objects. The endoscope is a vital tool for minimally invasive surgery. Because of its many advantages, the conventional endoscope system is becoming an important medical tool for diagnosing human diseases. However, sophisticated skills are necessary to operate the endoscope, and in conventional endoscopy considerable time is required for data acquisition. Moreover, the endoscopic

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*Corresponding author: e-mail: mems@chonnam.ac.kr inspection using the flexible tube is still very uncomfortable for patients. It is also not easy to inspect the inside of the small intestine using the conventional endoscope system. To overcome those drawbacks, capsular endoscope systems have been developed by several research groups.(1–3) Pill-size capsular endoscopes are convenient for patients and have no structural limitations, thus are able to reach the small intestine and duodenum. Hence, the capsular endoscope system overcomes the drawbacks of the conventional endoscope mentioned above. A recently developed capsular endoscope even allows doctors to examine the lining of the middle part of the gastrointestinal tract, which includes the three parts of the small intestine (duodenum, jejunum, ileum). To date over 400,000 patients worldwide have experienced the advantages of painless and effective capsular endoscopy.(1) However, most of the capsular endoscope systems including the PillCam™ capsular endoscope, which is a first-line tool in the detection of abnormalities of the small bowel, can only move by the force of intestinal motion because they cannot move by themselves. Hence, the capsular endoscope cannot retrace its path even if a doctor has missed important information during the endoscopy. This currently limits further applications of the capsular endoscope. Currently, many researchers are attempting to embed applicable functions into the capsular endoscope. Menciassi *et al.* proposed a locomotive mechanism for the capsule using shape memory alloys so that the capsule can move autonomously in the human body,(4) and Byun *et al.* introduced the spike, which is a type of biopsy needle.(5) Olympus Corporation introduced a capsular endoscope applying wireless power transmission technology.(2) The Intelligent Microsystem Center also developed a working robot for use with their capsular endoscope, MiRO.(6) Recently microelectromechanical-system (MEMS) technology has proven to be a key enabling technology for developments not only in advanced medical care but also in transportation and telecommunications. This is because MEMS technology opens up new possibilities of integrating motors, sensors, computation circuits and power supplies onto a single piece of silicon. Rethinking the use of micro- and nanotechnologies allows us to solve many problems that would not be possible to solve by conventional machining technologies.

In this paper, we describe new types of microactuator that require a large displacement such as a working robot for use with a capsular endoscope or an x-y microstage for nanolithography applications.(7,8) Several types of microactuator were designed and they were optimized by a finite element method. The designed microactuators employed the thermal expansion power of polydimethylsiloxane (PDMS), which has a high coefficient of thermal expansion. The thermal expansion coefficient of PDMS is 11 and 6 times larger than those of Al and polyimide, respectively. The moving mechanism of the microactuator was based on the movement of an inchworm, which can only move in the forward direction with the help of a specially designed sole of the foot. A study of the PDMS-based thermal microactuator was performed to evaluate its feasibility for further applications.

2. Design and Microfabrication of the Thermal Actuator

A MEMS-based bimorph actuator is a micromechanical device that typically generates motion by the thermal expansion of two materials with different thermal expansion coefficients. A small amount of thermal expansion of one part of the device translates to a large deflection of the entire device. The bimorph structure is often employed for actuator design. Many different designs have been proposed to improve the performance of the bimorph actuator. Some of them have already been applied in the field of MEMS.(9) However, the conventional structures of thermal actuators, particularly the bimorph structure, are not suitable for application to a working robot. As mentioned by Ebefors *et al.*,(10) the main problem associated with the fabrication of silicon-based robots is the realization of sufficient strength in their movable legs and rotating joints. This problem is caused by the moving mechanism of the thermal microactuator with the bimorph structure. For example, the thickness ratio of two materials must be optimized, but it is not easy to deposit a thick layer using the conventional fabrication technique. The spring constant of the actuator should be also minimized to obtain a large displacement, but the actuator cannot withstand a large loading mass. In other words, we may lose one quality or aspect upon gaining another quality. These restrictions mean that the realization of a bimorph actuator with sufficient strength and a large displacement is very difficult.

The new thermal actuator designs proposed in this study employed PDMS, which has a high coefficient of thermal expansion (approximately 310 ppm). The proposed actuator, which has a large volume, has the potential to solve the problems mentioned above. Figures 1(a) and 1(b) show schematic views of the PDMS-based thermal micro-actuator. The shape and locomotive mechanism of the thermal actuator are analogous to those of

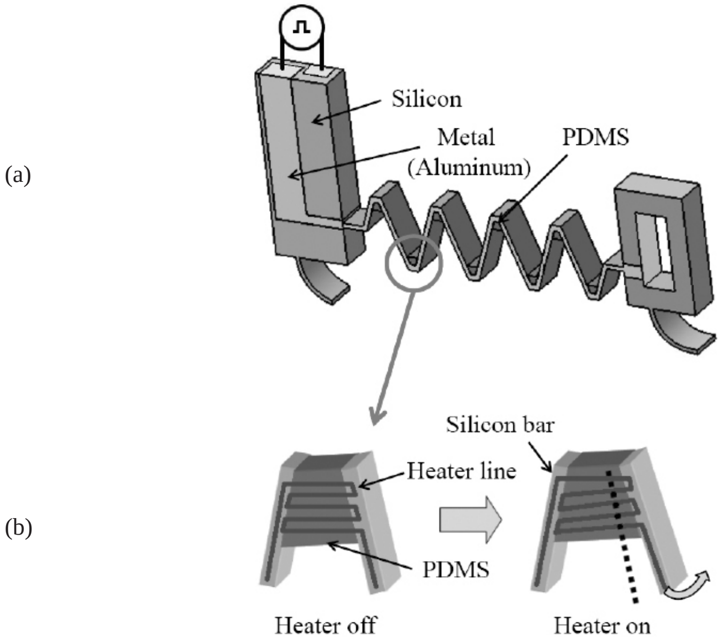


Fig. 1. Schematic diagrams of (a) PDMS-based microactuator and (b) thermal expansion of the PDMS joint area by Joule heating generated from an integrated heater.

a small inchworm. The PDMS-based thermal microactuator basically uses the thermal expansion power of PDMS (Sylgard-184 silicone elastomer) for locomotion. By driving the legs from right to left, the microactuator can move in one desired direction. The principle of motion of the PDMS actuator joint is shown in Fig. 2. The body undergoes thermal shrinkage in the left direction when the PDMS joint is electrically heated. The increase in temperature can be achieved internally by electrical resistive heating or externally by a heat source capable of locally introducing heat. An array of V-shaped PDMS joints provides much larger displacement than other microactuator structures. Living organisms are a good model for microactuator designs. For example, mimicking the way six-legged insects walk has been proposed for the design of multilegged robots, which were then demonstrated after implementation by microfabrication techniques. A walking silicon microrobot based on V-groove joints was also proposed in 1999.(10) Because of the simplicity of implementing MEMS technology, a similar principle to that mentioned above has already been used for microactuator applications. The implemented heater shown in Fig. 1(b) can be easily and simply turned on and off in capsular endoscope applications. Another advantage of the microactuator is that it can be modularized by connecting two or three bodies. The maximum displacement or force will be markedly increased by a combination of actuator modules in series or parallel.

In this study, we designed several structures for PDMS-based thermal microactuators. The optimum structure was determined by ANSYS, a numerical analysis method. We also confirmed that the displacement of each V-groove actuator has strong dependence on the silicon thickness at the articulated joint, called the V-groove joint. The maximum displacement was obtained by continually decreasing the silicon thickness at the joint. We thus designed joints with zero silicon thickness. Figure 3 shows the ANSYS simulation result for one of the actuator designs. Each PDMS joint had a displacement

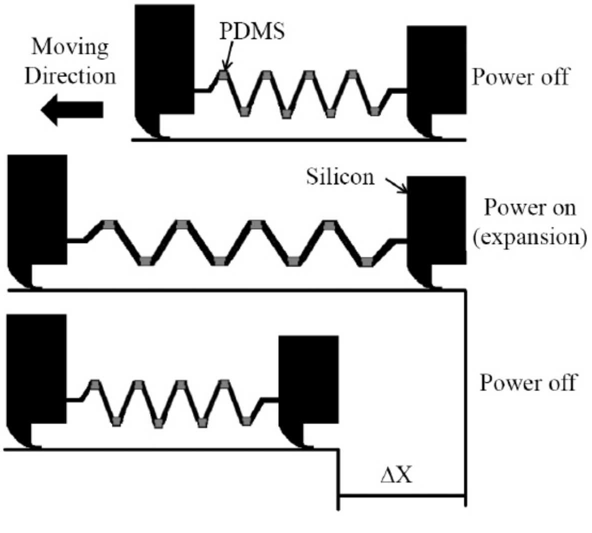


Fig. 2. Mechanism using the thermal expansion of PDMS joints. A specially designed sole of the foot helps the actuator to move in the forward direction.

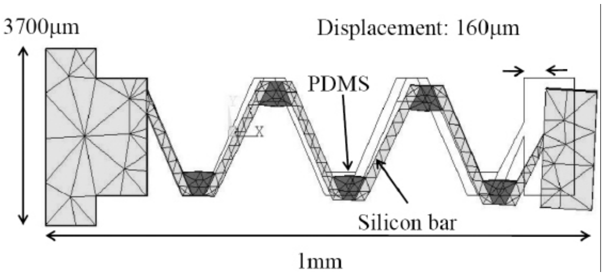


Fig. 3. Simulation result using ANSYS. The displacement of the actuator is about 160 μm at 300°C.

of ~32 μm at 300°C. The small amount of thermal expansion of the V-groove joint translated to a large deflection of the entire actuator.

The process flow for the fabrication of the PDMS-based actuator is illustrated in Fig. 4. Details of the process flow are described in ref. 6. To pattern both sides of the wafers, double-side polished wafers were used. Wafer orientation was not an important factor in our consideration, but low resistivity was vital to prevent undesired current flow to the body of the microactuator. First, a mask is used as a layer for making via holes by deep reactive etching. In this process, etch depths of hundreds of micrometers can be achieved with almost vertical sidewalls using an inductively coupled plasma reactive ion etching (ICP-RIE) system. After cleaning using piranha solution, the silicon wafer was thermally oxidized in steam. The thermally oxidized layer improves the adhesion of PDMS to the substrate. PDMS solution was then injected into the via holes formed by the first deep RIE process. To fill the etched holes with PDMS without any vacancies, we used a handmade 3D micromachining alignment system, which consists of a molding part and an aligning part. Details of the molding system are described in ref. 11. Next, a thin Al layer was deposited on both sides of the wafer. Metal lines and microheaters were defined by optical lithography using a second mask. Finally, the shape of the micro-actuators was fabricated by a second deep RIE process. An optical image of a fabricated microactuator is shown in Fig. 5.

3. Experimental Results and Discussion

Three different types of PDMS-based microactuator were evaluated using a simple experimental setup. As shown in Figs. 6–8, various structures of the PDMS part were designed to find an optimal structure that provides the largest deformation for a given power. Deformation of the PDMS structure during thermal heating generates movement of the microactuator in the forward direction. Type 1, shown in Fig. 6, is the basic structure. Type 2 is modified to compensate for the expected nonlinearity of type 1 during thermal actuation. The PDMS structures in types 1 and 2 were only placed at the areas of the V-groove joints. In the case of type 3, shown in Fig. 8, the whole structure is made of PDMS, hence it may provide much larger displacement than types 1 and 2. The high coefficient of thermal expansion of PDMS is another major advantage for its use in actuator applications. Conventional microactuators would become fatigued with

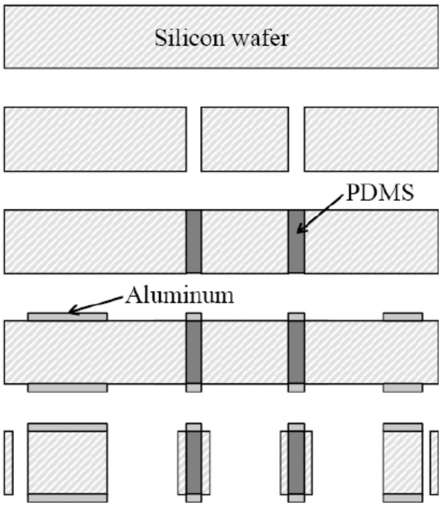


Fig. 4. Process flow for the PDMS-based microactuator fabrication.

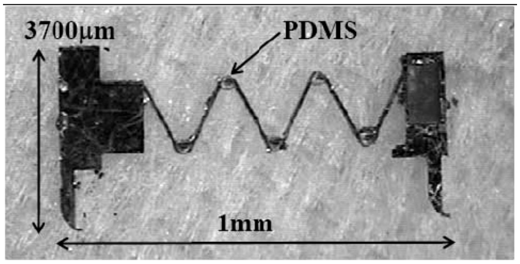
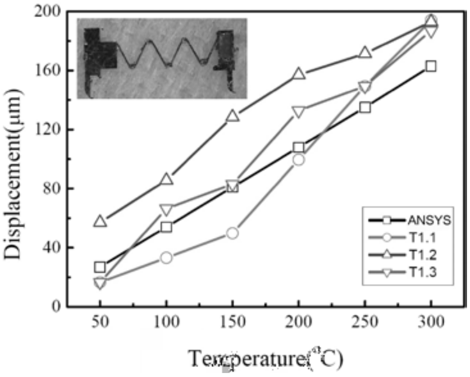


Fig. 5. Optical image of fabricated PDMS-based microactuator.

repeated operation since most microactuators are operated at a high frequency. However, PDMS is relatively resistant to fatigue and does not age or oxidize readily. This means that the PDMS actuator is very suitable for microsystems or actuator applications.

We first evaluated the maximum displacement of the fabricated microactuators. A microruler fabricated for this experiment was employed to measure precise displacements as a function of temperature. The microactuators were fixed in the perpendicular direction to the microruler, which was placed on a hot plate. Thermal power was applied to the microruler through the hot plate and was monitored using a temperature gauge. The temperature of the plate was gradually increased from room temperature to 300°C. The displacement of the actuators was observed using an optical microscope. The maximum displacement of the fabricated microactuators was also analyzed by placing them on the hot plate. Local heating of the microactuator produced the same effect as applying a current. Figures 6–8 show the experimental results (triangles and circles) of the three different actuators, and they are compared with the simulation results (squares). The simulation results of the three actuators are in good agreement with the experimental



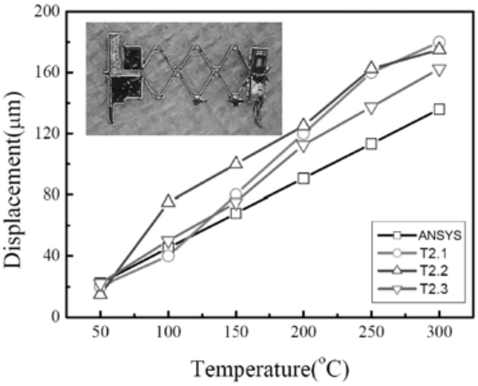


Fig. 6 (left). Actuator displacement as a function of applied temperature. The inset shows an optical image of the type 1 actuator.

Fig. 7 (right). Actuator displacement as a function of applied temperature. The inset shows an optical image of the type 2 actuator.

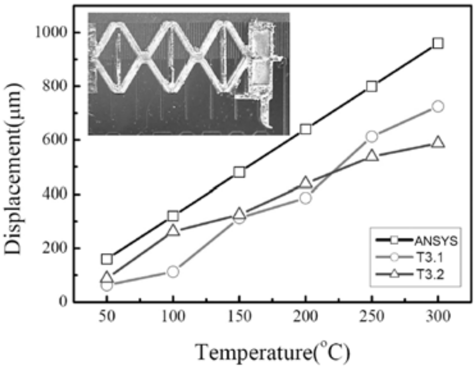


Fig. 8. Actuator displacement as a function of applied temperature. The inset shows an optical image of the type 3 actuator.

results. The average displacements of types 1–3 were 191 μm (0.63 μm/°C), 172 μm (0.58 μm/°C) and 656 μm (2.81 μm/°C), respectively. Small variations in the displacement of each actuator are due to the second deep RIE process, which has a different etch rate depending on the position on the wafer. The etch rate at the center of the wafer is much greater than that of other areas. This causes small changes in the PDMS shape and silicon joint structures. One of the type 3 fabricated micro-actuators had a maximum displacement of about 725 μm. The actuation velocity was also measured at different electrical powers and frequencies using the method described in ref. 6. The maximum working speed was observed at the first resonance frequency. Further optimization of the microactuator will allow its use in capsular endoscope applications.

4. Conclusions

In this study, we proposed and developed a new type of thermal actuator. The thermal expansion of a polymer, PDMS, was applied as the main principle in the actuator. PDMS is very suitable for actuators that require a large displacement. The structure of a microactuator with 1 mm length and 350 µm width was optimized by numerical analysis. The bottom sole of the actuator foot was specially designed to achieve sufficient movement for use in working robots and x-y stage applications. Three different types of thermal actuator were fabricated by conventional micromachining. One of the designed structures had a maximum displacement of about 725 µm. The experimental results were in good agreement with the simulation results. Maximum displacements or forces will be markedly increased by the combination of actuator modules in series or parallel.

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