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ScienceDirect
Microelectronic Engineering 84 (2007) 1278–1281
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

MEMS-based modular actuator for capsular endoscope applications

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Available online 2 February 2007

Abstract

In this study, we propose and develop MEMS-based modular actuators for self-movable capsular endoscope applications. A structure of the micro actuator of 1 mm length and 350 μm width is optimized by using numerical analysis. The bottoms of the actuator legs are especially designed to achieve sufficient moving force of the actuator in smooth environment. The shape of the PDMS actuator is variously designed and it placed several positions to find the optimal position that provides a high transformation ratio. Five different types of design for the PDMS actuator are suggested and analyzed by numerical analysis. The fabricated micro actuator was heated by using a hot-plate and supplied with voltage by using a function generator. Displacement of the micro actuator was measured as a function of temperature from 27 to 300 °C. Each of V-groove shaped joints was actuated about 28 μm at 300 °C. Another design of the micro actuator had a maximum displacement of about 500 μm. The new concept was proven to be very useful for actuators that require a large displacement.

Keywords: Actuator; PDMS; V-groove; Capsular endoscope

1. Introduction

A conventional endoscope is becoming an important medical tool for diagnosing human diseases. However, the sophisticated skills needed to operate an endoscope requires considerable time to learn acquire. Moreover, endoscopic inspection is very painful to patients. Second, it is really difficult to inspect inside the small intestine by using the endoscope. To overcome these problems, new capsular endoscopes, which moves by intestinal motion, have been recently invented by several research groups. Given Imaging Ltd. commercialized a capsule endoscope, M2A and PillCam [1], and the Olympus Corporation introduced a capsule endoscope that applies wireless power transmission technology [2]. The intelligent microsystem center developed their capsule endoscope, MiRO [3]. The pill size capsule endoscopes are convenient for patients and have no structural limit, fully able to reach the small intestine and duodenum. Hence, it overcomes the above-mentioned drawbacks of the conventional endoscope. Unfortunately, current technologies allow for only imaging and other functions such as surgery tools, and micro actuators should be incorporated for future applications. These days, many researchers are trying to embed these applicable functions into a capsule endoscope. Dario et al. proposed a locomotive mechanism for the capsule so that the capsule can move autonomously in the human body by using the shape memory alloys [4], and Cho et al. introduced a spike, which is a kind of biopsy needle for a capsule endoscope using MEMS technology [5].

However, capsular endoscopes still have a drawback, that is, it cannot move by itself when supplied with small power. Nowadays, MEMS has become one of the fastest growing areas of technology in this area. They have proven to be a key enabling technology in developments in areas such as transportation, telecommunications and advanced medical care. MEMS allow a new possibility by integrating motors, sensor, computation, and power supplies onto a single piece of silicon. Rethinking micro actuator technology can solve many disadvantages more cost effectively, albeit in novel ways. During the past 20 years, many different concepts for actuator design have been proposed for

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0167-9317/$ - see front matter
doi:10.1016/j.mee.2007.01.105

application in a working robot. However, to our knowledge, nobody has succeeded in achieving a working robot capable of carrying a capsular endoscope. As mentioned by Stemme [6], the main problem associated with the fabrication of silicon robots is the realization of sufficient strength in their movable legs and rotating joints.

In this paper, we have developed a PDMS micro-joint based on bulk micromachining, which can be used to develop motion systems using arrays of thick, erected, silicon legs. The micro actuator is steered only forward by the specially designed sole of the foot.

2. Design and fabrication

The shape of the designed modular actuator based on MEMS technology looks like an inch-worm. It has a same moving mechanism as the inch-worm. The micro actuator basically uses the thermal expansion of the PDMS (polydimethylsiloxane; sylgar®184 silicone elastomer) as its moving power. The PDMS with a high thermal expansion coefficient (approximately 310 ppm) is very suitable for micro actuators that require large displacements. Furthermore, it can facilitate the fabrication of a micro actuator. The PDMS is widely used as material for MEMS packaging [7], micro fluid channel [8], and nano imprint [9] applications. It is a useful material in MEMS. PDMS is a very soft material, providing high thermal expansion. Hence, it is very suitable in the manufacture of our micro actuator that requires a large displacement. A cross sectional view of the micro actuator is illustrated in Fig. 1a. By driving the right leg on the left, the micro actuator can move in one direction desired. The operation principle of the PDMS joints is shown in Fig. 1b. The body shows thermal shrinkage in the left direction, when it is heated locally by integrated Cr heaters placed on the PDMS joints. An array of V-shaped joints provides much larger displacement than other structures of a micro actuator. Living organisms are good model for micro actuator designs. For example, mimicking the way six-legged insects walk has been proposed and demonstrated for designs of multi-legged robots implemented by using microfabrication techniques. A walking silicon micro-robot based on V-groove joints is also proposed in 1999 [6]. Due to the simplicity of implementing MEMS-technology, a similar principle mentioned above is used in a level of design level for the micro actuator. As shown in Fig. 1b, the implemented heater can be easily and simply turned on and off for capsular endoscope applications. Another advantage of the micro actuator is that the micro actuator can be modularized by connecting two or three bodies. In this study, to design a micro actuator that can achieve maximum displacement, several types of micro actuators were designed, and the optimum design of their joints were found by numerical analysis. Fig. 2 shows the ANSYS simulation result and it is one of designed structures of the actuator. Each PDMS joint has a displacement of 34 μm at 300 °C.

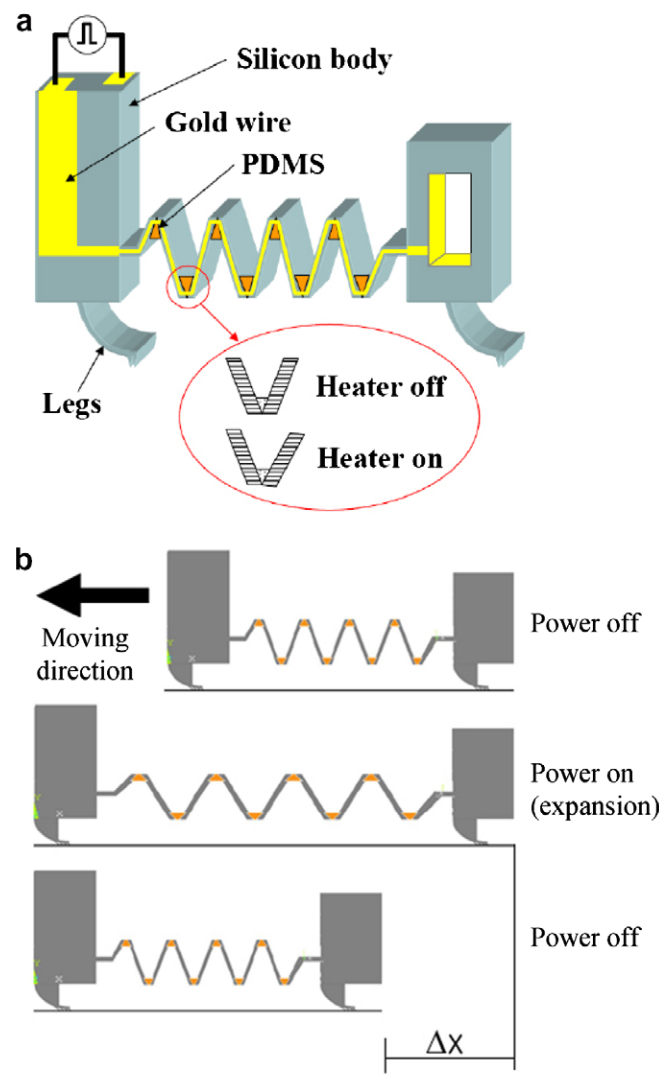

Fig. 1. (a) A concept of MEMS-based modular actuator and (b) the actuation mechanism using a thermal expansion of PDMS joints.

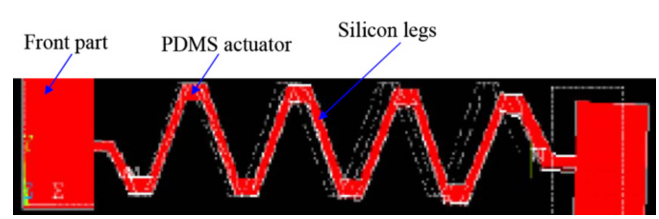

Fig. 2. Simulation results using ANSYS. The maximum displacement is about 242 μm for the micro actuator with 8 PDMS joints.

Process flow for the fabrication of the micro actuator based on the thermal expansion of the PDMS is illustrated in Fig. 3. We used three photo-masks and p-type wafers for the fabrication process. For patterning both sides of wafers, double-side polished wafer were used. Wafer orientation is not an important factor of consideration, but low resistivity is strongly desired to protect undesired current flow to the body of the micro actuator. The first mask defines the several types of a pattern with a thick photore-

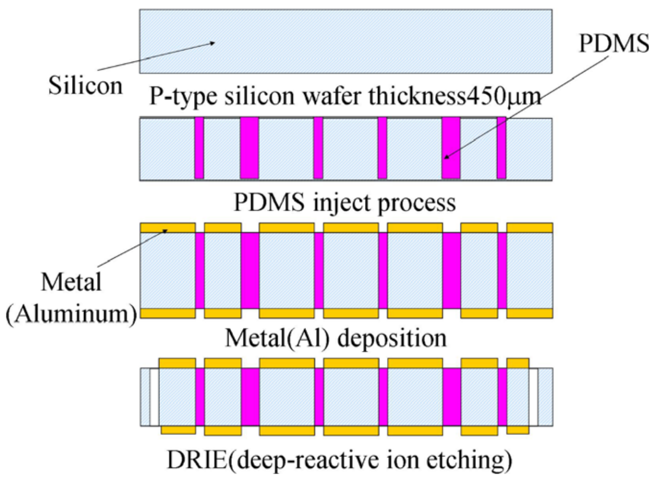

Fig. 3. Process flow for the micro actuator.

sist. It is used as a mask layer for making via holes by a deep reactive process. In this process, etch depths of hundreds of micrometres can be achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process", named after the German company Robert Bosch, in which the compositions of two different gases, SF_6 and C_4F_8, are alternated in the reactor. The C_4F_8 gas composition creates a polymer on the surface of the substrate, and the second gas composition etches the substrate with both energies of mechanical and chemical power. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls because reactive ions are accelerated to the sample surface with a high energy. Since the polymer dissolves very slowly only in the chemical part of the etching, it builds up on the sidewalls and protects them during the etching process. As a result, etching aspect ratios of 100–1 can be achieved. The process can easily be used to etch completely through a silicon substrate. The PDMS is injected into the through-holes made by the first deep RIE process. After the cleaning process with the piranha solution, the silicon wafer is thermally oxidized in steam. The thermally oxidized layer helps adhesions of the PDMS. In order to fill the PDMS in the through-holes, we used a handmade 3D-micromachining aligner system, which consists of a molding part and an aligning part. Top and bottom wafer chucks in the molding part are used to seat the respective molding masters. The surfaces of both chucks are coated with Teflon to allow easy separation of PDMS. The bottom wafer chuck lies on a bottom molding plate and is connected with a connection jig. Details of the molding system are described in Ref. [10]. The second mask defines metal lines and heaters by optical lithography and sputtering. The Au/Cr is about 200/100 nm in thickness and 100 μm in width. By removing the Au layer only at the heater area, the Cr layer can be used as heater material for joule heating. It can transfer the thermal energy to the PDMS. The final mask is employed for the second deep RIE process, which shapes the micro actuator. Optical images of before and after the deep RIE process for the micro actuator fabrication are shown in Fig. 4. The fabricated micro actuator is 1 cm in length and 500 μm in height.

3. Experimental results

Measurement and characterization of the PDMS based a micro actuator were evaluated. The maximum displacement of the fabricated micro actuator was analyzed by heating it on a hot-plate and supplying it with voltage with a function generator. We first fixed the actuator on the hot plate to evaluate its displacement as a function of temperature. The front end of the micro actuator was completely fixed on the stage with a ruler. Temperature was gradually increased from room temperature to 300 °C, and the actuator's displacement was observed by using an optical microscope. Heating the actuator produced the same actuation effect as applying a current to the micro actuator. Fig. 5 shows the experimental results (blue squared and pink triangle) and they are compared to the simulation results (red circle). The simulation results were in good agreement with the experimental results. However, each micro actuator fabricated in the same wafer showed small differences in displacement due to small variations in the alignment process. The actuation velocity was measured at different electrical powers and frequencies. The maximum working speed was observed at the first resonance frequency. This speed was limited by the maximum supply voltage allowed to the Cr heater. Higher speeds are therefore possible by changing the heater material. The maximum displacement obtained was about 54 μm (;) however, most of the micro actuators yielded a displace-

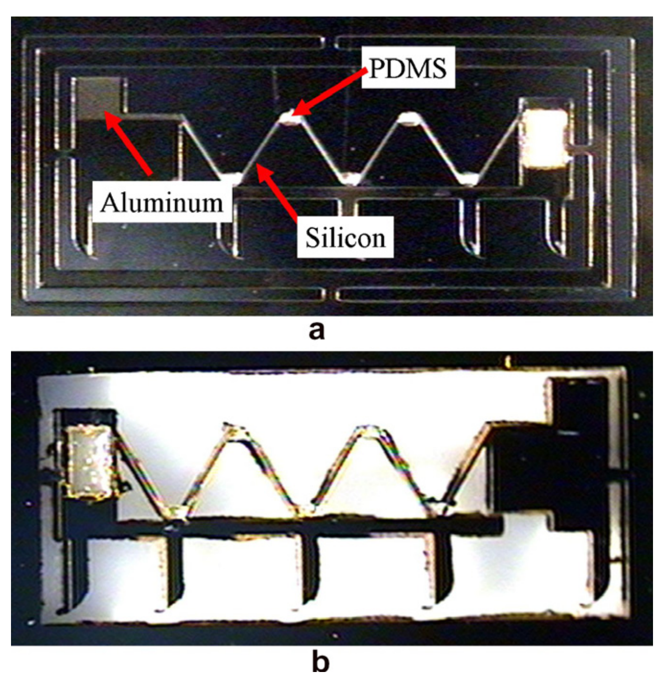

Fig. 4. Optical images of (a) before and (b) after the final DRIE process.

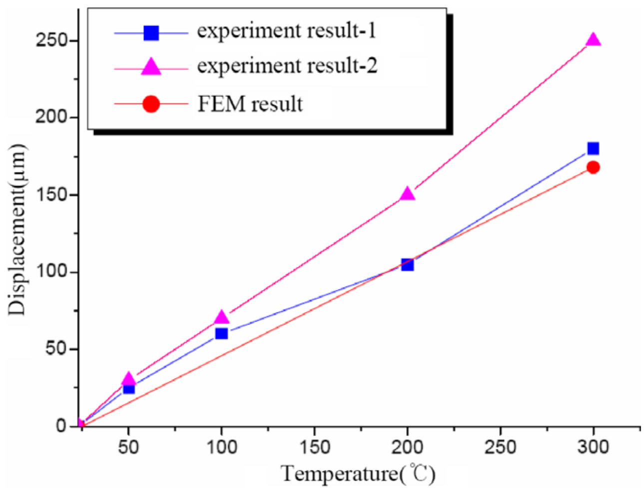

Fig. 5. Micro actuator displacement as a function of temperature applied to the PDMS joints.

ment of about 30 μm at 300 °C. We are currently trying to integrate the micro actuator under the capsular endoscope developed by Intelligent Microsystem Center in Korea.

4. Conclusion

In this study, we proposed and developed MEMS-based modular actuators for self-movable capsular endoscope applications. A structure of the micro actuator of 1 mm length and 350 μm width was optimized by numerical analysis. Bottoms of the actuator legs were specially designed to achieve sufficient movement in the smooth environment. The position of the PDMS was variously designed and placed to find the optimal position that would provide a high transformation ratio. Five different types of design were suggested and analyzed by numerical analysis. Each of V-groove shaped joints was actuated about 28 μm at 300 °C. A different design of the micro actuator gave the maximum displacement of about 500 μm. Compared to other proposed approaches applied to produce a micro working robot, our approach produces a robust micro actuator. It can give the high load capacitor. Hence, this approach can be effectively implemented to move the capsular endoscope.

Acknowledgements

This research has been supported by the Intelligent Microsystem Center (IMC; http://www.microsystem.re.kr), which carries out one of the 21st century's Frontier R&D Projects sponsored by the Korea Ministry Of Commerce, Industry and Energy.

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