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A WALKING SILICON MICRO-ROBOT

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ABSTRACT

The first walking batch fabricated silicon micro-robot able to carry loads has been developed and investigated. The robot consists of arrays of movable robust silicon legs having a length of 0.5 or 1 mm. Motion is obtained by thermal actuation of robust polyimide joint actuators using electrical heating. Successful walking experiments have been performed with the 15x5 mm^2 sized micro-robot. Walking speeds up to 6 mm/s with high load capacity has been achieved. The robot could carry a maximum external load of 2500 mg on its back (> 30 times the dead-weight of the robot).

INTRODUCTION

In the famous talk by R. Feynman "… the problem of manipulating and controlling things on small scale" using micro-machines was addressed for the first time [1]. These problems were further discussed ten years ago at the MEMS'89 workshop by Barret *et al.* [2]. They discussed the benefits of scaling down the rest of the subsystems of a robot to the same scale as the control systems. By integrating motors, sensors, computation and power supplies onto a single piece of silicon, enormous advantages can be obtained in the form mass producability, lower costs and fewer connector problems encountered when combining discrete subsystems. This kind of silicon microfabricated robot-system follows the definition of a true `micro-robot´ according to Dario *et al.* [3]. The robot by Barret *et al.* [2] is classified as a `miniature robot´ not a `micro-robot´. Rethinking the robot technology can solve many problems more cost effectively, albeit in novel ways [2, 3].

During the past 10 years, many different concepts have been proposed to realize silicon micro-robotic devices. To the best of our knowledge, nobody has yet succeeded in achieving a walking microfabricated micro–robot capable of carrying large loads. The main problem associated with the fabrication of silicon robots is to achieve enough strength in the movable legs and in the rotating joints. Most efforts to realize micromachined robots utilize surface micromachining techniques which results in thin and fragile legs. Pister *et al.* proposed surface micromachined micro-hinges for joints, poly-Si beams for legs and linear electrostatic stepper motor actuation for the realization of a micro-robot [4]. Bright *et al.* has made prototypes of micro-robots using thermal actuation of thin manually erected silicon legs [5]. Miura *et al.* introduced the concept of creating insect-like micro-robots with exoskeletons made from surface micromachined polysilicon plates and polyimide joints [6]. The flexibility of polyimide makes it a suitable micro-joint material [6]. Allen *et al.* demonstrated another type of actuator based on polyimide joints using electrostatic actuation [7]. However, the drawback with that solution is the difficulty to integrate the actuators in array configurations. Furthermore, it may be problematic to create true three dimensional structures which can be rotationally well controlled out-of-plane.

We have recently developed a new robust and self-assembled polyimide micro-joint based on bulk micromachining which is suitable for the realization of micro-motion systems using arrays of thick erected silicon legs [8-10].

As a step towards the goal of creating autonomous wireless silicon micro-robots we present the worlds first walking micro-robot fabricated with a monolithically silicon batch-fabrication process. The applications for such micro-world operating, potentially low-cost robots include the assembly of a whole microsystem from different microcomponents (i.e. micro-factories), tools for assembling and testing electronic circuits, and new tools for microsurgery.

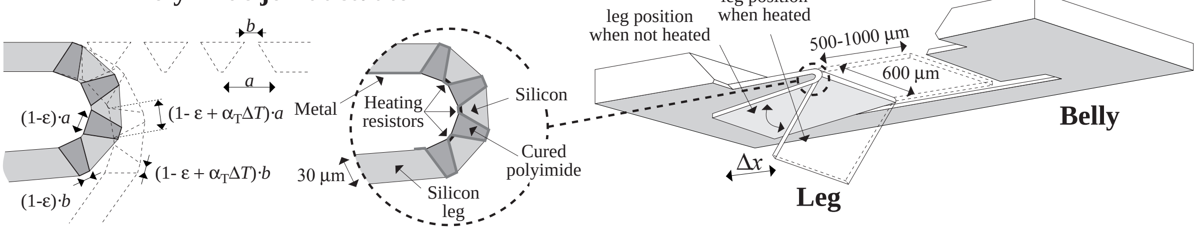

Fig. 1. *Design and actuation principle for the leg movements based on a four V-groove joint. By heating the joint a horizontal displacement, Δx, is obtained due to larger absolute thermal expansion of the polyimide at the top of the V-groove than at the bottom ($\alpha_T \cdot \Delta T \cdot a > \alpha_T \cdot \Delta T \cdot b$).*

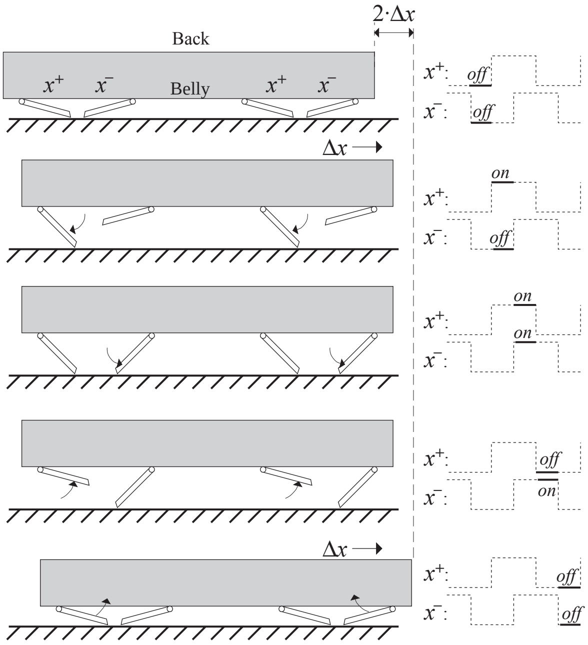

Fig. 2. *Operation principle for the asynchronous driven micro-robot. A displacement equal to* $2\cdot\Delta x$ *is obtained during one period due to the fixed phase difference of 90 degrees between the two sets of legs (*x^+ *and* x^-*). A 180 degrees phase-shift between* x^+ *and* x^- *will results in walking in the opposite direction.*

PRINCIPLE

The operation principle of the polyimide joint actuator is shown in Fig. 1 [8-10]. The legs are rotated out-of-plane (the self-assembled static mode) due to thermal shrinkage (ε) when the polyimide in the V-grooves is cured. By using polysilicon heaters, local heating is achieved in the joint resulting in thermal expansion ($\alpha_T\cdot\Delta T$) of the polyimide (the dynamic mode). The V-shape of the joint allows for a larger absolute expansion length at the top of the V-groove than at the bottom resulting in a dynamic motion, Δx.

Living organisms offer good models for designing micro motion systems [11, 12]. Mimicking the way six-legged insects walk has been proposed for designing multi-legged robots implemented using microfabrication techniques [5, 12]. The first proposed [13] and realized [11] micro motion system (i.e. conveyance system) was based on the ciliary motion principle adopted from nature. Due to the simplicity of implementing MEMS-technology, the same principle is used in this work. The simple on-off actuator control can be easily realized with saturated FET-transitors eliminating the need for integrating electronics on the micro-robot itself. The basic principle of the asynchronously driven one dimensional micro-robot is shown in Fig. 2. The robot is steered forward and backward by changing the phase-shift between x^+ and x^-. The robot is steered in the right-left directions by driving the left and right legs at different speeds or stroke length (in the same way a caterpillar does).

Fig. 3 illustrates the robot dimensions and the layout of the legs.

FABRICATION

The fabrication process is schematically shown in Fig. 4 [10, 14]. The key steps are: **(*a*)** forming the integrated heater using LPCVD-deposited poly-silicon encapsulated in low-stressed silicon nitride and anisotropic KOH etching of 30 μm deep V-grooves. **(*b*)** local silicon dioxide (LOCOS) growth, forming via holes to the heaters, patterning the 1.5 μm thick aluminium conductors deposited by sputtering. **(*c*)** spinning and patterning the polyimide in the V-grooves, a backside 500 μm KOH silicon etch. **(*d*)** dicing the robot (from the back-side), a BHF oxide etch and solvent cleaning to release the 30 μm thick silicon legs and the protecting wafer, finally a polyimide curing in an oven to erect the legs.

Several different versions of the micro-robot have been fabricated:

- Polyimide joint actuator variants: with 3 and 4 V-grooves
- Leg variants: 2x6 with a length of 500 μm and 2x4 with a length of 1000 μm
- Steering variants: two groups of four or six legs (3 bonding pads for back and forth) and four groups of two or three legs (5 bonding pads for back and forth + right and left)
- Two DOF-legs (both knee and ankle joint) for walking up/down steps or on rough surfaces.

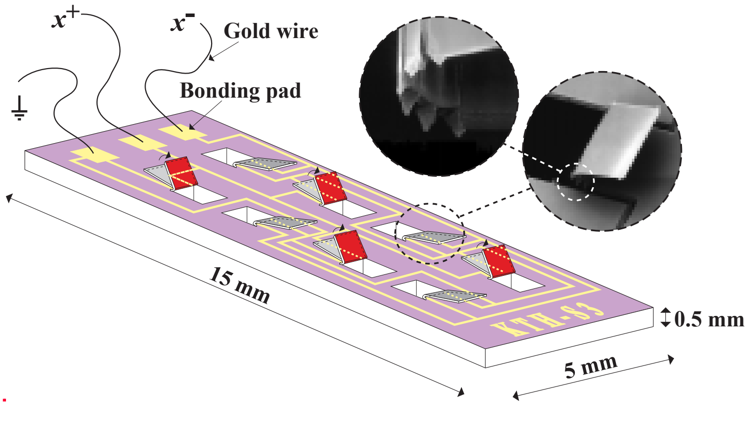

Fig. 3. *An up-side down view of the micro-robot with two set of legs (four of each* x^+ *and* x^-*). With three bonding pads the robot can walk forward and backward. By driving the legs on the left and right side at different speeds or stroke length like a caterpillar (requires 5 wires) the robot can make left-right turns. The SEM-photos show silicon leg with a length of 500 μm and a close-up of a five V-groove polyimide joint.*

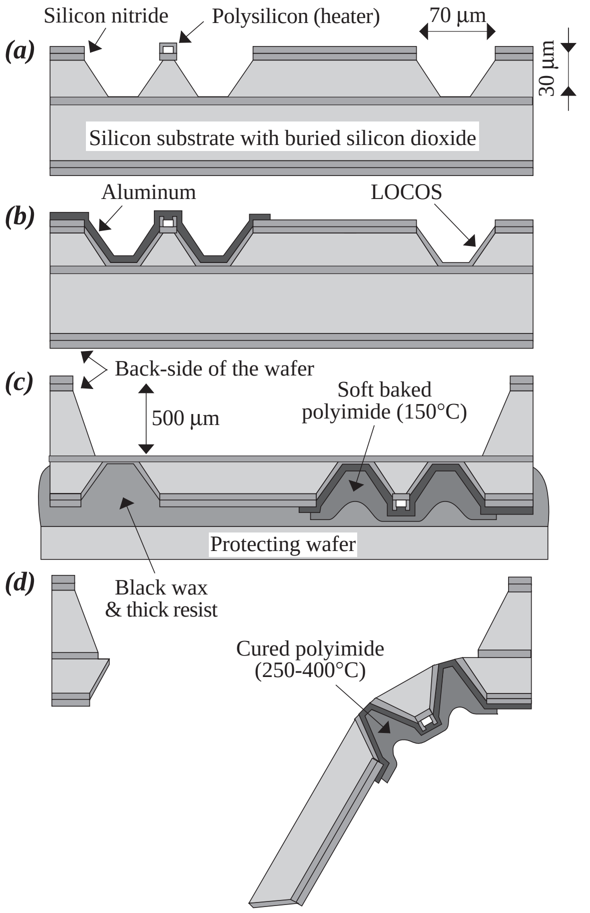

Fig. 4. *Schematic of the fabrication process based on SOI-wafers.*

EXPERIMENTAL RESULTS

Measurements and characterization of the polyimide joint actuators concerning speed (actuation frequency), power consumption, strength, robustness and failure mechanisms has been presented earlier [8-10] and are partially summarized in Table 1.

The long-time performance of the polyimide joint actuators was investigated in an accelerated life-time study [10]. The actuators were still working without degradation after more than $2 \cdot 10^8$ load cycles (equal to a walking distance of approximately 7,000 meters).

To evaluate the function of the new micro-robot, basic walking experiments were performed on an isolated (SiO_2-covered) non-polished silicon wafer with the micro-robot shown in Fig. 5. This forward and backward walking robot consists of eight silicon legs (arranged in two groups of four legs). The leg length is 1 mm and the legs are connected to the robot body by polyimide joints containing three V-grooves having a static bending angle just under 90°. The different joints are thermally actuated using the asynchronous driving mode described in Fig. 2.

Table 1. *Characteristic measurements of the polyimide joint actuators.*

Curing temp, T / shrinkage, ε	350 °C / 40% (3 V-grooves) 280 °C / 30% (4 V-grooves)
Life-time	$> 2 \cdot 10^8$ load cycles
Stroke length, Δx / power consumption, P	< 340 µm / < 175 mW (for 1 mm leg with 4 V-grooves)
Cut-off frequency, f_c	3 – 4 Hz (-3 dB)
Force / displacement (before plastic deform.)	50-100 mN / 250-400 µm

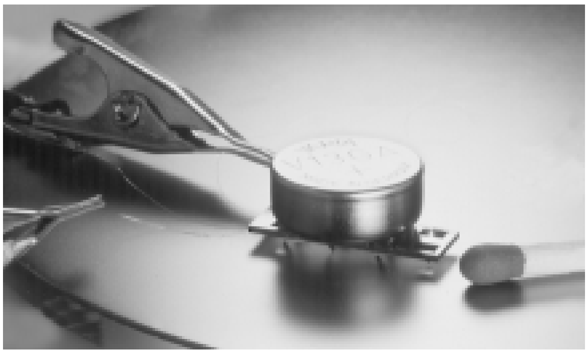

Fig. 5. *The micro-robot during a load test. The load of 2500 mg is equivalent to maximum 625 mg/leg (or more than 30 times the weight of robot itself). The power supply is maintained through three 30 µm thin and 5 to 10 cm long bonding wires of gold.*

The velocity was measured at different powers, loads and frequencies, as shown in Fig. 6. The maximum measured walking speed was 6 mm/s at an applied squared voltage of 18 V (approximately 1.1 W) and a frequency around 100 Hz. This speed limit was set by the maximum supply voltage allowed by the electronic circuits we used and not by the polyimide joint actuators. Higher speeds are therefore possible to achieve by increasing both the heating power and the frequency. During the first measurements the walking distance was limited to a couple of centimeters by the length of the gold wires used for the power supply.

Temperature variations in the polyimide during the actuation cycle are dependent on the frequency [10]. For frequencies above the cut-off frequency, f_c (where the stroke length Δx is reduced by –3 dB), the thermal mass of the polyimide counteracts fast heating and cooling which reduces the maximum temperature (and increases the minimum temperature). Therefore, it is possible to compensate for the small displacements at

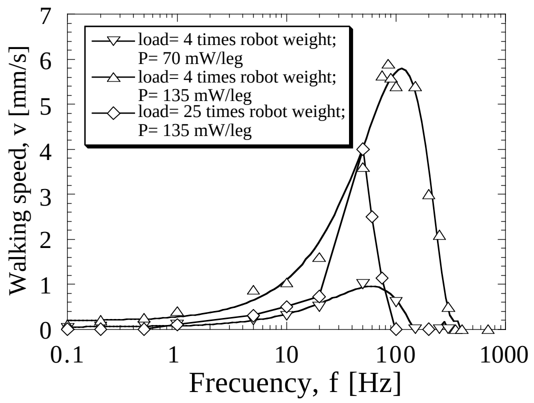

Fig. 6. *Walking speed as a function of frequency for different loads and power.*

higher frequencies by increasing the heating power without going over the maximum temperature at which the joints are destroyed. The walking speed increased with increased power as illustrated in Fig. 6. The walking speed also increases with frequency up to a specific frequency where the maximum speed is achieved. Due to small variations in the static leg position, the robot could not move at all at very high frequencies due to the small displacements of the leg. The leg has to overcome both the surface roughness (approximately 2-5 μm for the unpolished silicon wafer) and the variations between the different static leg position.

By increasing the load to 25 times the dead-weight of the robot itself, an unwanted reduction of the stroke length for each leg resulted. This translates into a lower walking speed and a lower top frequency at which the robot stops to walk.

The steering function of the robot has been demonstrated experimentally. There are four different approaches to steer the micro-robot to the left and right by imitating a caterpillar:

- phase: one side is driving forward and the other side is driving backwards.
- power: longer strokelengths (Δx) on one side by increasing the power (also means higher steps (Δy) => the robot walks with a stoop).
- frequency: increasing the number of steps on one side (means smaller steps (Δx and Δy) => the robot walks with a stoop).
- combination of frequency and power: (equal strokelength but faster on one side => “smooth” robot movements).

DISCUSSION

Compared to other proposed approaches to realize micro-robots, the main advantage of our technique is the robustness of the actuators which gives the high load capacity. Besides the robust actuator function achieved with our approach, the polyimide joint principle also has the advantage of being self-assembled. Other proposed robot approaches [4-6] need time- and cost-consuming manual assembly to erect the leg from the wafer (robot body). The large displacement (or stroke length) of the silicon legs when using our polyimide joint actuators results in a fast robot which is relatively insensitive to the topography of the surfaces. Furthermore, the robot can walk on both conducting and non-conducting surfaces [6].

The bonding wires limit the miniaturization of the robot to approximately 10x5 mm^2. For smaller robots the stiffness of the bonding wire affect the motion too much. This is in agreement with the results of other micro-robot where a 10x10 mm^2 robot could not walk because of the wire stiffness [5]. Therefore, we think we have reached the size limit for micro-robots steered and powered through bonding-wires. However, the challenge and the possibility of making smaller autonomous wire-less (i.e. battery powered and telemetric steered) robots still remains.

CONCLUSION

This paper has presented the first batch fabricated walking silicon micro-robot capable of carrying loads. The polyimide joint based robot could carry loads more than 30 times the dead-weight of the robot itself. The maximum measured walking speed was 6 mm/s with potential to improve by modifying the steering. The challenge for the future is to create tele-operated and autonomous micro-robots on a single silicon chip.

ACKNOWLEDGEMENT

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