MICRO-FINGER ARTICULATION BY PNEUMATIC PARYLENE BALLOONS

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ABSTRACT

Articulated micro-fingers have been developed as an important building block to construct micro-robotic end-effectors such as a micro-hand. This micro-finger features robust finger segments made from bulk silicon, pneumatically driven balloon joints made of Parylene thin film, and monolithic integration to minimize leakage. We present the device concept, joint mechanism, and fabrication processes, as well as test results. For the current specification, each finger is measured to exert over 0.15 mN at 120 psi.

INTRODUCTION

Micromanipulators, designed to handle objects in microscale, have long been popular in MEMS. An example is the MEMS microgripper actuated by various mechanisms. Electrostatic comb-drive actuation was used for a polysilicon microgripper that successfully grabbed a dried Euglena [1]. An electromagnetic microgripper was developed to hold a 100 μm diameter sea urchin egg [2]. Other actuation mechanisms include thermal actuation [3] and shape-memory-alloys [4]. However, they are either ineffective in ion-rich fluid or consume a high amount of energy and affect the surroundings. Since most of the micro objects are in biological fluids in practice, an actuation mechanism inert to the surroundings is desired.

Pneumatic actuation has gained its ground in recent years because of its inertness to the surrounding environment, especially in liquids [5][6]. We have previously reported a pneumatically driven multi-fingered microcage, mimicking the sea anemone entrapping its prey with its tentacles (Figure 1) [6]. The device was made of twelve bimetallic fingers, curled up by their residual stress mismatch, on a rubber membrane. The microcage opens when the rubber membrane bulges under pressure and closes when the membrane springs back by releasing the pressure, as shown in Figure 2 (a). While demonstrating successful trapping of live organisms floating in liquid, the microcage was not designed to apply any force. For more general micro-robotic application where forces need to be applied (e.g. micro-surgery), much stronger fingers with dexterity are desired.

Figure 2 explains the differences. The microcage in Figure 2(a) is a device that opens by actuation but closes as a result of the structural stiffness. Its maximum grasping force is simply the spring back force of the structure at the moment. On the other hand, the micro-hand in Figure 2(b) is a device that closes by actuation and opens as a result of the stiffness. Its grasping force can be controlled by the actuation pressure. Moreover, the articulated fingers add some dexterity compared with the fixed curls in Figure 2(a). The active-grasping micro-hand design shows promising improvement over the passive-trapping microcage design.

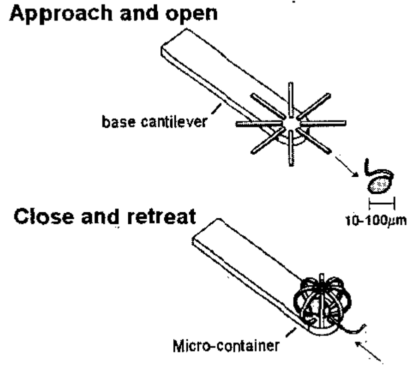

Figure 1. Schematic view of microcage operation [6].

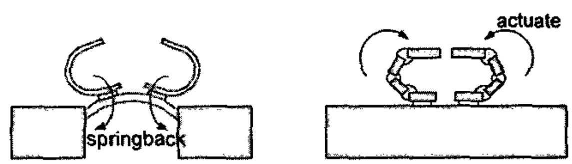

Figure 2. Microcage and micro-hand. (a) Microcage made of thin film fingers on flexible membrane [6]. (b) Micro-hand made of articulated fingers and active joint.

The pneumatic manipulation tools reported so far are mostly made by manual-assembly [7][8]. Rubber balloons and necessary pneumatic channels were glued to silicon blocks [7]. We expect reliability will be a major problem in the assembled devices, which are likely prone to leakage and peeling. They are also in millimeter scale and not suitable to handle micro-objects below the realm of today's commercial microsurgical tools.

DESIGN CONCEPT

A device consisting of articulated microfingers, monolithically joined by active Parylene balloons and made by silicon batch processing, is proposed. Each

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microfinger is a functional element featuring DRIE-patterned bulk silicon blocks (segments) connected by pneumatic balloon joints. Figure 3 illustrates a micro-hand with four fingers. Once the balloon joints are actuated (pressurized), the silicon blocks will rotate out-of-plane and the micro-hand closes. This is attractive because it provides us a strong finger structure and allows us to control the grabbing force with actuation pressure.

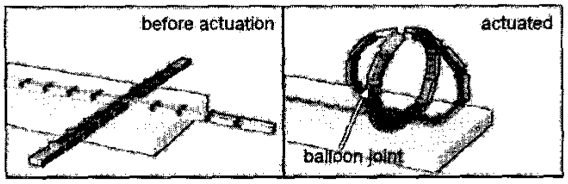

Figure 3. Articulate fingers closed by inflating balloon joints for large-force applications such as microsurgery (artist's view).

Figure 4 illustrates the operation of such balloon-jointed microfingers. The balloons are in a deflated state and the microfinger is in the neutral position as fabricated. When the balloons are inflated, the silicon blocks rotate out-of-plane. The entire pneumatic network, including balloons and channels, is made of Parylene thin film and the channels are partially imbedded in silicon.

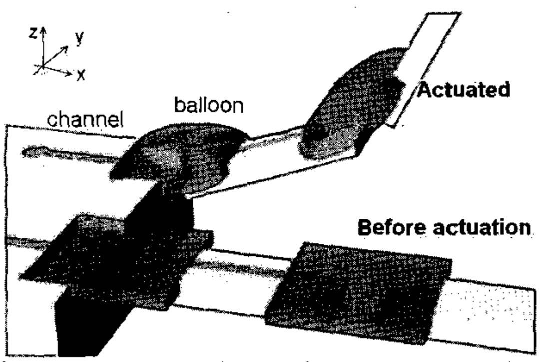

Figure 4. Schematic view of fingers, Parylene balloon joints and pneumatic connections.

WORKING PRINCIPLE

The working principle of the pneumatic balloon joint can be explained with a simplified centimeter-scale experiment in Figure 5. A flat plastic bag is attached to two plates at a certain distance from the butting edges. When air inflates the bag round, the distance between the two attached points is shortened, making the two plates angled and generating the out-of-plane rotation This actuation is a contraction movement and is similar to the grasping motion of human fingers. The angle between the two planes increases with actuation pressure until it reaches a saturation value.

The saturation angle of each balloon joint is the function of the geometry of the balloons and silicon blocks. Their relative width and length play important roles in the final rotation angle of each joint. The overlapping and overhanging width and length, shown in Figure 6,determine how much out-of-plane rotation each balloon joint can have. The widthwise overhang of the balloon is necessary in balloon joint design because it allows the top surface of the balloons to have the freedom to move up and become round so that the two attached points AA' in Figure 5 get closer. The more overhanging width the balloon has, the more each joint rotates.

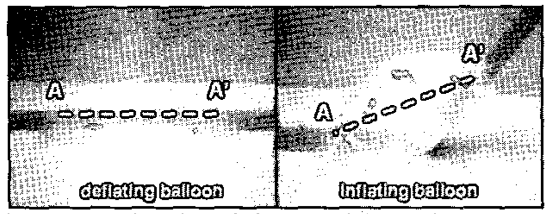

Figure 5. Principle of balloon joint. Distance AA' decreases when the balloon is inflated.

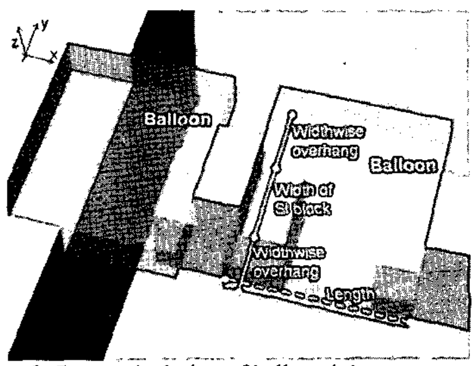

Figure 6. Geometric design of balloon joints.

FABRICATION PROCESS

The fabrication processes are outlined in Figure 7. (1) They start with thermal oxidation for 1000Å thick Oxide and LPCVD deposition for 1200Å thick Nitride on a 200 μm thick silicon wafer. The first lithography on the backside and DRIE make 150 μm deep trenches with 50 μm thick silicon remaining. (2) The second lithography and RIE on the front side make the 4x4 μm grid holes on Oxide/Nitride films. (3) These grid holes then allow XeF_2 to isotropically etch the silicon underneath and form 30 μm deep cavities that subsequently define balloons and channels for pneumatic actuation and connection. (4) Vapor-phase deposited Parylene conformally coats the inside walls of the cavities as well as the top Oxide/Nitride surfaces through the 4x4 μm holes. These tiny holes are eventually sealed by Parylene. The Parylene film is then patterned by O_2 RIE etching. (5) A final releasing step by XeF_2 removes the remaining 20 μm silicon from backsides and completes a balloon-jointed silicon block.

SEM pictures in Figure 8 show an overall top view of a microfinger (left) and a bottom view of the Parylene balloon and its surroundings (right).

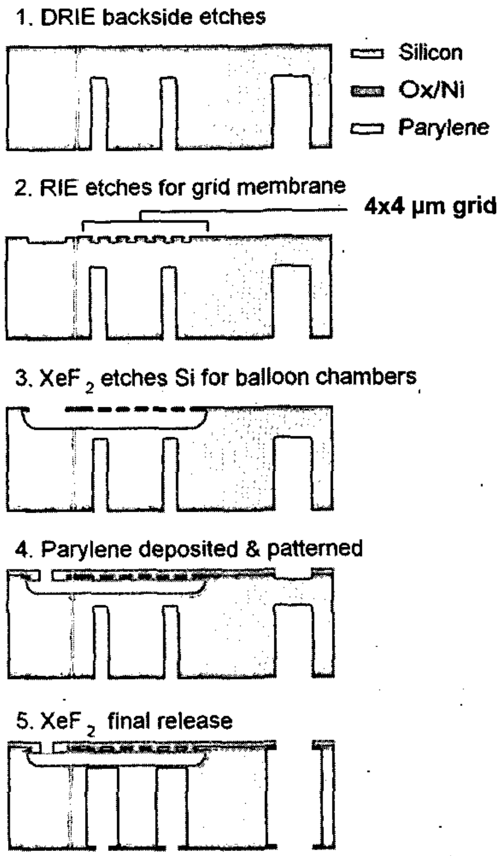

Figure 7. The process flow of the device.

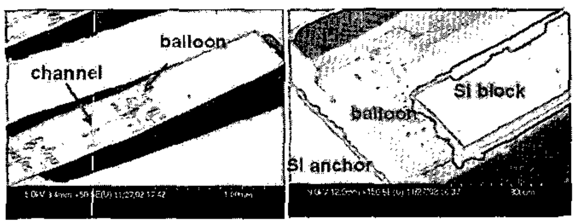

Figure 8. The front (left) & bottom view (right) of a completed finger by SEM.

BALLOON FORMATION

There are several key steps in making the Parylene balloon. First, the silicon cavity defines the balloon and channel. The cavity is formed by XeF_2 that diffuses through an array of 4x4 µm holes, spaced by 12 µm on Oxide/Nitride thin film. XeF_2 etching initially forms small cavities under the holes but connects them into a continuous channel with balloons after enough etching. Secondly, it is necessary to deposit a proper thickness of Parylene because Parylene balloon walls grow while the grid sealing process progresses. The sizes of the grid holes define the wall thickness of the Parylene balloons. Smaller grid holes make balloons too thin and weak. On the other hand, the bigger grid holes make sealing difficult and the resulting balloon too rigid. The Parylene film thickness is chosen as 6 µm on the top surface to completely close the grid holes of 4x4 µm. Parylene balloon becomes about 2 µm thick on the side and the bottom. The SEM picture in Figure 9 visually confirms the sealing of such a grid hole.

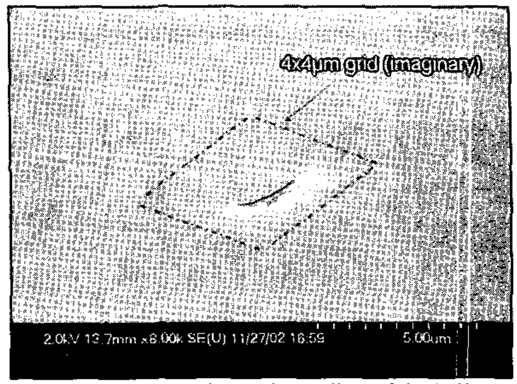

Figure 9. SEM picture shows the sealing of the balloon.

EXPERIMENT AND RESULTS

I. Experimental Setup

The current micro-hand device consists of four fingers in a cross pattern. Each finger has three 900x300 m silicon blocks connected by 540x640 m Parylene balloons in-between. The balloons are pneumatically actuated through the microchannels in silicon. For the experiment, the device on the chip is mated with a separately machined Plexiglas piece that provides the pneumatic interface to the external pressure source. The package of the micro-finger is schematically shown in Figure 10.

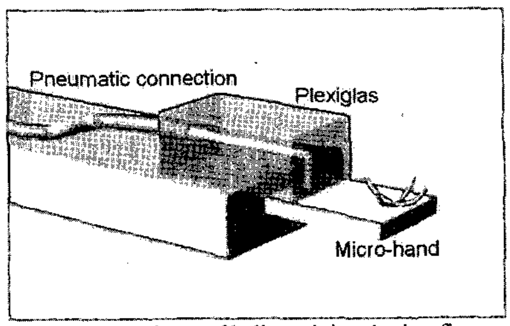

Figure 10. The package of balloon-jointed microfingers.

II. Actuation Test

Figure 11 is the preliminary actuation test of this microfinger device that is pneumatically operated from 0 psi to 120 psi. The tip of each microfinger rotates out-of-plane about 40 degrees. The response of the microfinger actuation follows the control signal of the pneumatic valve very well without any noticeable delay.

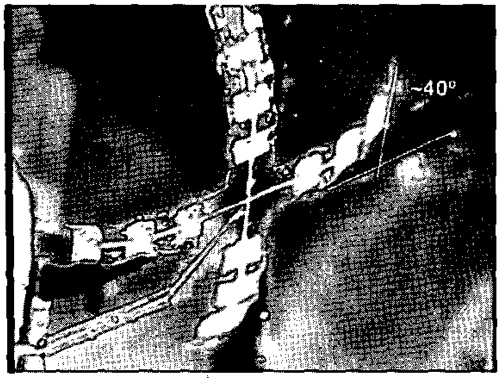

Figure 11. The device is actuated to 40° of tip angle at 120 psi.

III. Weight-Lifting Test by Microfinger

The device of four microfingers in cross pattern has been pneumatically actuated. A 60 mg (~0.6 mN) washer is loaded on the microfingers to show the force in Figure 12. Each microfinger is averaged to exert about 0.15 mN. The microfingers showed little difference in out-of-plane rotation with and without loadings. It can lift up the washer about 300 μm high at 120 psi. This result demonstrates the strong force capability of the balloon-jointed microfingers.

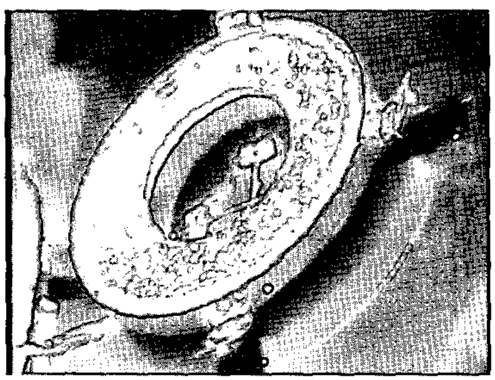

Figure 12. The device lifts a 60 mg washer up ~300 μm at 120 psi.

SUMMARY AND FUTURE WORK

A pneumatic balloon joint mechanism has been successfully applied to articulated microfingers for active micro-hands. The actuation mechanism of inflating balloons provides active grasping and large forces, while the monolithic balloon fabrication makes structurally robust joints. Large force and flexible structures are desirable in micro actuators and suggest many useful biomedical applications such as microsurgery and biopsies.

Current work focuses on the strength characterization and the design optimization for larger out-of-plane rotation without decreasing the applied force. The eventual goal is to utilize the micro-hand for biological samples, where tissues are detached from organs/organisms, for example, and integrate it with commercial microsurgery tools.

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