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# Silicon End-Effectors For Microgripping Tasks

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## Abstract

Micromanipulation is a key task to perform serial assembly of MEMS. The two-fingered microgrippers are usable but require specific studies to be able to work in the microworld. In this paper, we propose a new microgripping system where actuators and the end-effectors of the gripper are fabricated separately. End-effectors can thus be adapted to the manipulated micro-objects without new design and/or fabrication of the actuator. The assembly of the end-effectors on our piezoelectric actuators guarantee a great modularity for the system. This paper focuses on the original design, development and experimentation of new silicon end-effectors, compatible with our piezoelectric actuator. These innovative end-effectors are realized with the well known DRIE process and are able to perform micromanipulation tasks of objects whose typical size is between 5  $\mu m$  and 1  $mm$ .

*Key words:* Microgripper, micromanipulation, end-effectors, MEMS assembly

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## 1. Introduction

There are several ways to assemble micro-objects (micro-assembly). First, batch assembly with flip-chip processes is commonly used in MEMS production. It allows to build planar MEMS by the assembly of several planar components. It is especially used when microfabrication processes of two different micro-parts cannot be realized on the same substrate. Secondly some research teams improve methods to assemble microproducts by self-assembly methods. In this case, micro-objects are driven by non-contact forces or capillary forces in the required position. This parallel assembly principle allows to position a large number of objects simultaneously but the efficiency is mainly low and several objects do not reach their final position at

all [1]. Serial assembly is a third approach which is used for more complex out-of-plane structures or prototyping. In this case, innovative robots have to be able to manipulate micro-objects with a high accuracy. The study of new micromanipulation methods continues to be a big issue for the development of serial assembly nowadays.

The major difference between micromanipulation and manipulation at macroscopic scale concerns the nature of predominant forces applied to the objects. The volume forces (weight, inertia) are indeed negligible in respect to the surface forces (pull-off force, electrostatic forces, etc.) for microscopic objects. These forces, whose effects are negligible on a macroscopic scale, drastically modify contact behavior [2-6].

These surface forces may affect micromanipulation tasks, especially grasping and releasing. The success of this kind of task depends on several parameters like the materials, the size of both the micro-gripper and the object, the nature of surrounding medium (vacuum, air, liquid). Some han-

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dling micromanipulation strategies are currently being studied to propose an innovative principle adapted to the microworld (capillary grippers, ice grippers, adhesion grippers, etc.). The two-fingered microgrippers are usually used, but require a specific design to be able to manipulate micro-objects despite adhesion.

This article deals with a new type of two-fingered microgripper which is able to handle micro-objects whose size is lower than  $100\ \mu\text{m}$ . The second section is focused on the modular approach of the gripper. The third section deals with the architecture of the end-effectors and the fourth describes their mechanical design. Finally a fifth section presents the fabrication and experimentations to conclude in the last section.

## 2. Modular Architecture of the Gripper

Microtweezers which are capable of manipulating objects up to  $100\ \mu\text{m}$  are usually realized in monobloc structures using standard microfabrication techniques. In this case, end-effectors (in contact with the manipulated object) and actuators (able to induce the movement of the end-effectors) are built in the same fabrication process. This monobloc approach has two major drawbacks:

- As the adhesion between the end-effector and the object could perturb the release of the object, the design (size, roughness) of the end-effectors must be carefully studied for every type of object. Consequently, a monobloc gripper including actuators and end-effectors must be redesigned and fabricated for every type of application.
- The reliability of MEMS microfabrication process is lower and lower when the complexity increases. The structures of the actuators are usually more complex (eg. electrostatic actuator including electrodes, mechanical spring, etc.), than the design of the end-effector (eg. a simple beam). Consequently, in a fabrication batch of monobloc grippers, a lot of actuators are not efficient despite the fact that end-effectors could be used.

To overcome both drawbacks, we propose to manufacture actuators and end-effectors separately and to assemble them together to build the whole gripper.

To perform gripping actuation, we currently use a duo-bimorph piezoelectric actuator [7]. Developed in our institute and called MMOC (*Microprehensile Microrobot On Chip*) [8], this actuation principle al-

lows open-and-close motion as well as up-and-down motion. The structure of the actuators has been designed to use different end-effectors, called *finger tips*. They are temporary fixed onto special pads at the end of piezoelectric actuators by a removable thermal glue [9]. Initially, nickel end-effectors of a thickness of  $180\ \mu\text{m}$  (figure 1) were designed and produced with LIGA<sup>1</sup> process. They enabled the manipulation of objects whose typical size is below  $100\ \mu\text{m}$ . This article focuses on the design of new end-effectors which are able to manipulate objects up to  $100\ \mu\text{m}$ .

As the behavior of the micro-objects under  $100\ \mu\text{m}$  is dominated by surface and contact forces, performing manipulation under this limit is a great challenge [10]. Surface forces must be reduced to ensure that micro-objects can be released after the handling. Four aspects can be taken into account: reducing gripper surface, texturing gripper surface, controlling the environment, and/or using a physical principle to overcome adhesion.

In this article, we propose new end-effectors which have adapted shape and textured surface to reduce adhesion. To increase the number of application fields, the end-effectors are able to operate in different environments like air, vacuum or liquids. There are great interests in bioengineering for handling micro-objects in biological liquids [11]. Moreover, an original solution to reduce perturbations in microassembly tasks is based on performing tasks in a liquid medium which is able to decrease both surface and contact forces [12-14].

The innovative end-effectors compatible with the MMOC microactuators and immersible in various liquid media, are described subsequently.

## 3. Architecture of the End-effectors

The proposed end-effectors have to be able to manipulate objects whose typical sizes are between  $100\ \mu\text{m}$  and a few micrometers. The design requires the definition of material constraints associated with the fabrication processes and the required mechanical behavior for micro-manipulation tasks.

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<sup>1</sup> RontgenLithographie, Galvanoformung, Abformung - Lithography, Electroforming and molding

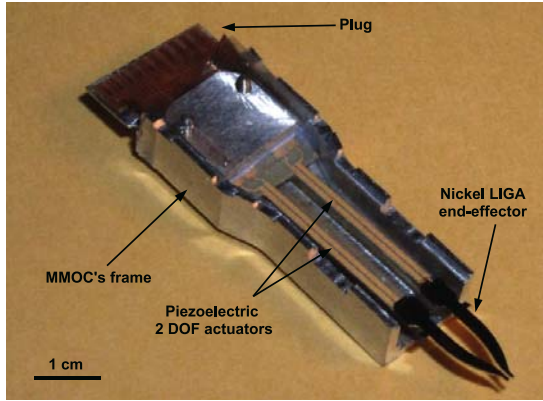


Fig. 1. MMOC microgripper with previous end-effectors in nickel.

### 3.1. Materials and Microfabrication Capabilities

As regards the material of new end-effectors, two parameters must be taken into account: the mechanical properties (material, geometry) and the micro-machining capabilities. First, a piezoelectric actuator cannot be immersed, thus end-effectors must be sufficiently long to have their extremity fully immersed and their base safely in the air. Therefore the capillary distance and the depth of the liquid medium must be taken into account to define the length of the end-effectors. Secondly, to manipulate micro-objects, the width and the height of end-effectors must be up to  $100\ \mu\text{m}$ , so microfabrication is the only way to produce this kind of mechanical object. Thus, the material has to be compatible with microfabrication processes.

Consequently, there are few materials which can be used, and crystalline silicon is one of the best choices. In fact, silicon has great mechanical features in the microworld: its Young modulus is 20% lower than structural steel and its yield stress  $1.2\ \text{GPa}$ [15] is two to four times greater than structural steel. Concerning liquid compatibility, only a few liquids like TMAH, KOH or EDP<sup>2</sup> are incompatible with silicon[16].

### 3.2. Architecture of the End-effectors

The shape of the end-effectors must be defined according to their main functions. The gripping sur-

face has to be adapted to the size of the micro-objects. If the end-effectors are as twice as thick or more than the grasped micro-object, it is practically impossible to see the latter. The end-effectors could in fact hide the grasped object because of the light diffraction and the very small depth of focus (about a few micrometers in microscopical vision). According to the main objective of this work, minimum size of the object is  $10\ \mu\text{m}$ . So the thickness of the end-effectors has to be close to this value.

When micromanipulation is performed in liquid medium, end-effectors must generate minimum disturbance. Large geometry at liquid interface generates large liquid medium flow and capillary effects. Then the grasping part of the end-effector is long and thin to go through the liquid medium (about one millimeter). Furthermore, end-effectors have to be mounted manually on the microgripper with a removable thermal glue. The surface of the glued part is consequently close to  $1\ \text{mm}^2$  with a length of a few millimeters for manual handling.

Considering these constraints, the design of the end-effector is composed of two thicknesses of silicon (close to  $10\ \mu\text{m}$  and  $1\ \text{mm}$ ) and both parts, thin and thick, are a few millimeters long. Several mechanical studies were made to estimate the deformation of the grasping part during micro-manipulation. The final design (figure 2) is presented in the following part.

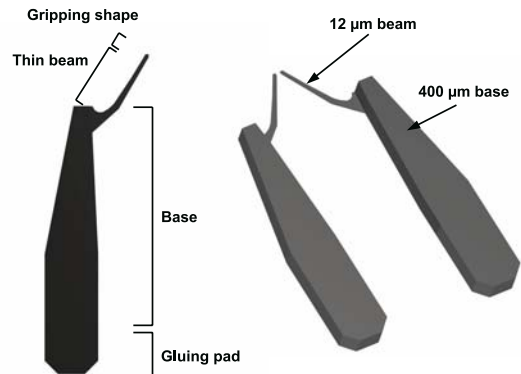


Fig. 2. New design of the end-effectors

## 4. Mechanical Design of the End-effectors

The design of the structure at this scale is highly dependent on microfabrication technologies. The

<sup>2</sup> TMAH: Tetramethylammonium hydroxide, KOH: potassium hydroxide and EDP: ethylene diamine and pyrocatechol

thin part of the designed end-effectors is a silicon beam whose length is at least 1 millimeter and thickness is around  $10 \mu m$ . To build this kind of silicon structure, we held silicon on insulator wafers (SOI) with two layers of polished monocrystalline  $\langle 100 \rangle$  silicon whose thicknesses are  $12 \mu m$  (device layer) and  $400 \mu m$  (handle layer), separated by a layer of buried oxide of a thickness of  $1 \mu m$ . The thick part of the end-effector was etched in handle layer, and the thin part in device layer. Detailed fabrication processes are presented in the next section. Finally, the studied beam has a thickness of  $12 \pm 0.2 \mu m$ .

The aim of this study is to determine geometrical dimension of the thin beam. The maximum strain it can handle during micromanipulation tasks is taken into account. The field of view is highly reduced during micromanipulation. It is a consequence of using photonic microscopes. When the view is focused on the gripping part of the end-effectors, the gripper may collide with an obstacle. Thus, it is important that they are able to endure sufficient strain before breaking down. Finally, the maximum strains on the two directions of the beam have to be defined, and geometric parameters can be calculated.

#### 4.1. Theoretical Study

This study is divided into two subsections. First, a preliminary analytical calculation is conducted to obtain basic dimensions of the beam of the end-effectors. Then, an optimisation with finite element simulation was performed to obtain the final design of the beam.

The geometric parameters of the Beam are shown in figure 3. Maximum strain in Z was defined to allow large beam deflection relative to its size, maximum deflection before breaking must be up to 1 mm:

$$\delta z_{max} \leq \delta z_{lim} \quad \delta z_{lim} = 1 \text{ mm} \quad (1)$$

For strain on Y axis, i.e. in gripping direction, maximum deflection must be twice as great as the maximum gripping deflection of the piezoelectric actuator, this ensures maximum security for silicon end-effectors:

$$\delta y_{max} \leq \delta y_{lim} \quad \delta y_{lim} = 300 \mu m \quad (2)$$

Deflection  $\delta z$  of the beam in function of the applied force is defined by:

$$\delta z = \frac{Fl^3}{3EI} \quad (3)$$

$$\sigma_{max} = \frac{Flh}{I} \quad (4)$$

where  $E$  is the Young modulus (150 GPa) of the silicon,  $I$  inertia moment on force direction,  $F$  is the applied force and  $\sigma_{max}$  the maximum yield stress (about 1.2 GPa). The maximum deflection  $\delta z_{max}$  verifies:

$$\text{from (3) and (4)} \quad \delta z_{max} = \frac{2}{3} \frac{\sigma_{max} l^2}{Eh} \quad (5)$$

From (1) and (2):

$$\frac{2}{3} \frac{\sigma_{max} l^2}{Eh} \geq \delta z_{lim} \quad (6)$$

$$\frac{2}{3} \frac{\sigma_{max} l^2}{Ew} \geq \delta y_{lim} \quad (7)$$

The third constraint which is brought about microfabrication is that the height is necessarily the wafer thickness:

$$h = 12 \mu m \quad (8)$$

To maximize gripping force, we have chosen to maximize end-effectors mechanical stiffness in both directions:

$$k_z = \frac{F_z}{\delta z} = \frac{3EI_z}{l^3} \quad \text{with} \quad I_z = \frac{wh^3}{12} \quad (9)$$

$$k_y = \frac{F_y}{\delta y} = \frac{3EI_y}{l^3} \quad \text{with} \quad I_y = \frac{hw^3}{12} \quad (10)$$

The optimal solution which maximizes  $k_z$  and  $k_y$  and respects constraints (6), (7) and (8) is done by:

$$l = \sqrt{\frac{3}{2} \frac{\delta z_{lim} E h}{\sigma_{max}}}$$

$$w = \frac{\delta z_{lim}}{\delta y_{lim}} h$$

So, numerical values are:

$$l = 1.5 \text{ mm}$$

$$w = 90 \text{ }\mu\text{m}$$

Thus, maximum forces are:

$$Fz_{max} = 1.7 \text{ mN} \quad (\text{vertical force})$$

$$Fx_{max} = 13.0 \text{ mN} \quad (\text{gripping force})$$

Preliminary sizing of the beam by analytical study is done, the shape can now be optimized by using FEM simulation.

#### 4.2. Optimization by FEM Simulations

Beam geometric parameters are now defined to respect the security of the end-effectors. However, a simple embedded beam is not the best shape for our gripper. Maximum stress is highly localized around the fixed end of the beam. For fragile materials like crystalline silicon, it is better to spread stress all over the beam. Therefore, the mechanical study has been completed with finite element simulation.

In primary design the two fingers are parallel thin beams, embedded on a thick structure. As the gap between both beams is only  $50 \text{ }\mu\text{m}$ , a small orientation default can extremely disturb the gripping. In fact, if the beams are not parallel, both thick structures could be in contact before the end-effectors of the gripper (thin beams) are closed. We proposed to tilt the gripping beam relatively to X axis with an angle of 30 degrees. So thick structures are far from each other.

To spread the maximum stress zone on the beam, we proposed to adapt the shape of the end of the fixed beam. The beam was then stretched and curved to evenly spread the maximum stress. Several designs were simulated under COMSOL<sup>TM</sup>, and the chosen solution is presented figure 4.

## 5. Fabrication and Experimental Results

### 5.1. Microfabrication Process

Considering design parameters and material requirement, silicon has been chosen for new end-effectors. SOI wafers, combined with appropriate microfabrication processes, enable the fabrication of our two-layered finger tips. Indeed, each silicon layer of the wafers can be etched separately: the

handle layer ( $400 \text{ }\mu\text{m}$ ) for the base of the finger and the device layer ( $12 \text{ }\mu\text{m}$ ) for the gripping beam. Some dry and wet etching processes were considered, and finally DRIE<sup>3</sup>, with BOSCH<sup>®</sup> process was chosen for three main reasons.

Firstly, this dry process is perfect to deeply etch silicon, with a good anisotropy. Secondly, the BOSCH<sup>®</sup> process is also very fast, with etching speed around  $6 \text{ }\mu\text{m}/\text{min}$ . Thirdly, the etching side has a particular roughness, called scalloping, as a result of the way of guaranteeing etching anisotropy. This roughness (figure 5) presents an interest to reduce gripping surface between silicon finger tips and manipulated micro-objects [17].

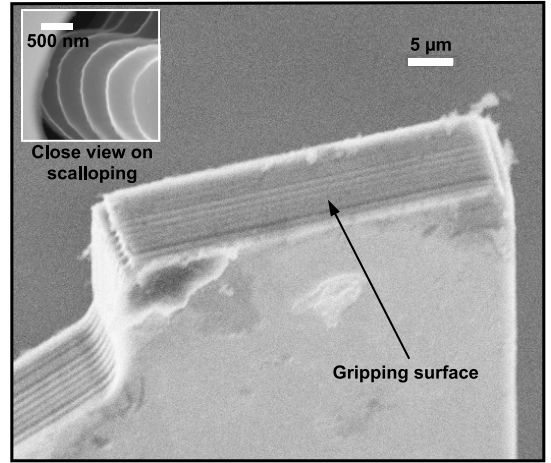


Fig. 3. View of the manipulation surface of the gripper. Focused view on the roughness of the surface after DRIE process.

The microfabrication flowchart presented in figure 6 was used to manufacture end-effectors called SiFiTs (Silicon Finger Tips). Metallic layers of aluminium and chromium were sputtered on both sides of the SOI wafer to mask silicon during DRIE. The pattern of the SiFiT was etched in metallic layers by positive photolithography. DRIE was firstly applied on the front side and then on the reverse. Finally, structures were released after metal stripping and  $\text{SiO}_2$  etching.

More than 90% of structures were fully operational and many gripping shape were available. An example of end-effector is proposed in figure 7.

<sup>3</sup> Deep Reaction Ionic Etching

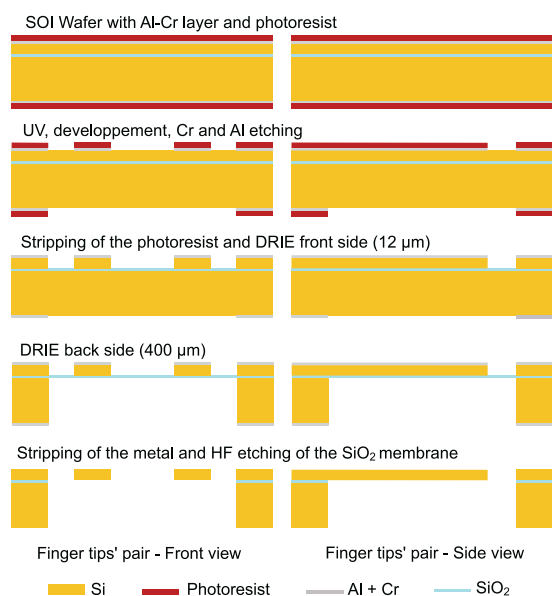


Fig. 4. Flowchart of the fabrication process of the end-effectors.

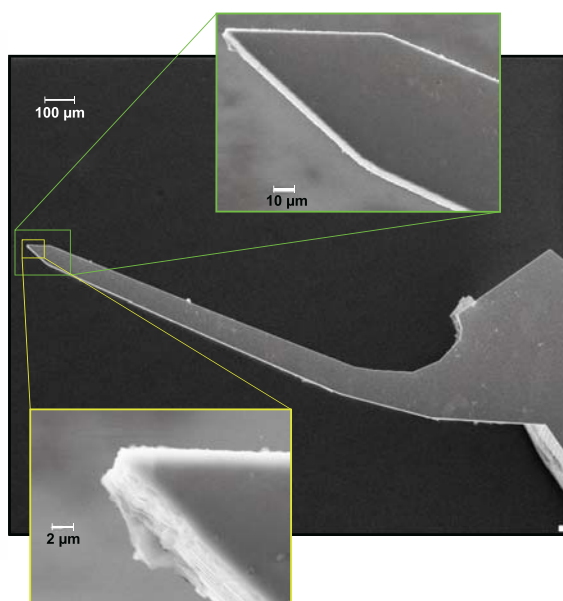


Fig. 5. SEM view of end-effectors

## 5.2. Gripping Experiments

Performing micromanipulation tasks requires the assembly of SiFiTs on the piezoelectric microgripper. This operation is currently carried out by an operator below a stereo microscope. Finger tips are fixed onto the actuators of the gripper with a

thermal glue, whose melting temperature is close to  $70^\circ\text{C}$ . It is obvious that manual operation brings positioning defaults during SiFiTs fixing procedure. This error is estimated at  $10\ \mu\text{m}$  on a horizontal plane and  $100\ \mu\text{m}$  on a vertical direction. However, the MMOC piezoelectric microgripper enables 2 DOF movements by finger tips. So it is possible to correct these defaults with the appropriate control of the actuator.

Micromanipulation tasks are performed on a platform which consists in 3 linear motorized stages. The human operator observe the scene via two videomicroscopes placed above and beside the micromanipulation area. A MMOC microgripper with SIFIT tools is used to handle micro-objects (figure 8). The operator teleoperates all the station with a joystick connected to the control computer.

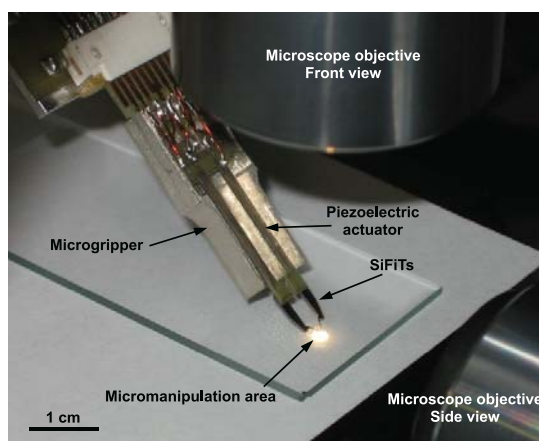


Fig. 6. Close view of the micromanipulation station

Finally, many micro-objects were gripped and released successfully in tele-operated pick and place tasks (see examples of micromanipulation in figure 9 and microassembly in [17]). They are enumerated in table 1. The Impact of both the size of the micro-objects and the manipulation medium on the success rate of the pick-and-place operations will be done in future work.

## 6. Conclusion

Micromanipulation is a key feature to perform precise assembly of micro-components. But performing micromanipulation requires *ad hoc* tools including high precision actuators and micrometric

| Shape            | Material    | Typical size ( $\mu\text{m}$ ) |
|------------------|-------------|--------------------------------|
| Spheric          | Glass       | $\Phi$ 5 - 200                 |
| Parallelepipedic | Glass       | 200                            |
| Parallelepipedic | Silicon     | 100 - 600                      |
| Parallelepipedic | Silicon     | 10 - 50                        |
| Crystallin       | Silicate    | 7 - 50                         |
| Cylindric        | Optic fiber | $\Phi$ 150                     |

Table 1  
Micro-objects used for SiFiTs experiments.

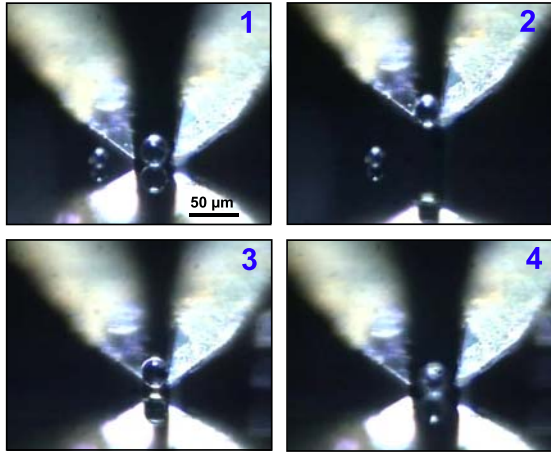


Fig. 7. Experimental pick and place of a 25  $\mu\text{m}$  diameter glass sphere.

finger tips. Then silicon finger tips of 12  $\mu\text{m}$  thickness, 90  $\mu\text{m}$  width and 1.5 mm length with different gripping surfaces were designed and manufactured. They are fully adapted for handling, in different media, micro-components whose typical size is between 5 to a few hundreds of micrometers. Many experiments were performed in both the air and a liquid medium to validate this microgripping principle. In further work, we will study a closed-loop control for this gripper to perform automated pick and place tasks. Integration of force sensors on the end-effectors will also be studied.

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