

Analysis and Characterization of an Electro-thermal Silicon-SU8 Micro-Gripper

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Abstract—This paper presents the analysis and measurement of a micro-gripper with both in-plane clamping as well as out-of-plane manipulation capabilities. A theoretical model, based on constraint polymer theory and mechanical analysis, has been used to investigate the influence of important factors on the performance of the device. The thermal behavior of the device is analyzed with FEA simulation. Measurement shows that each gripper arm performs a $7.4 \mu\text{m}$ in-plane and $14 \mu\text{m}$ out-of-plane motions at 1.6 V and 2.5V actuation voltage, respectively. The maximum temperature and power consumption are $180 \text{ }^\circ\text{C}$ and 26.5 mW for the in-plane and and $80 \text{ }^\circ\text{C}$ and 87.3mW for the out-of-plane actuator.

Index Terms—MEMS Micro-Gripper, Polymer Actuator

I. INTRODUCTION

Micro-particles and living cells manipulation pose great technical challenges for the design and implementation of micro-grippers. Many approaches have shown the possibility of handling micro-particles with sizes of several hundreds nanometers to tens of microns using MEMS grippers [1]. In order to achieve a better flexibility during the handling of the micro-particles, more degrees of motion freedom need to be integrated into the system.

This paper focuses on a micro-gripper with both in-plane clamping as well as out-of-plane manipulation capabilities. The proposed device consists of two arms, each driven by two electro-thermal actuators (Fig.1). The two in-plane actuators [2], located on the left and right hand side of the device, expand in the x direction to push the arms against each other, performing the clamping motion. The two out-of-plane actuators with bimorph structures [3], drawn on the top-left part of the figure, generate downwards bending motion, pushing each arm in the z direction. The device is thus capable of picking up an object from the working plane, move it and place it at another location.

Both types of actuators employ silicon-SU8 laterally stacked structures as a combined material. This has many advantages, such as a large effective coefficient of thermal expansion (CTE), a high Young's Modulus and a fast heat transfer.

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Aluminum wires are located on top of the silicon serpentine plates, working as heaters. The out-of-plane actuator contains an extra bottom layer, made from aluminum, under the silicon-SU8 block, in order to perform the bimorph bending motion. All of these actuators generate large motions at low voltage and at low temperature by utilizing the constraint polymer effect. [2&3]

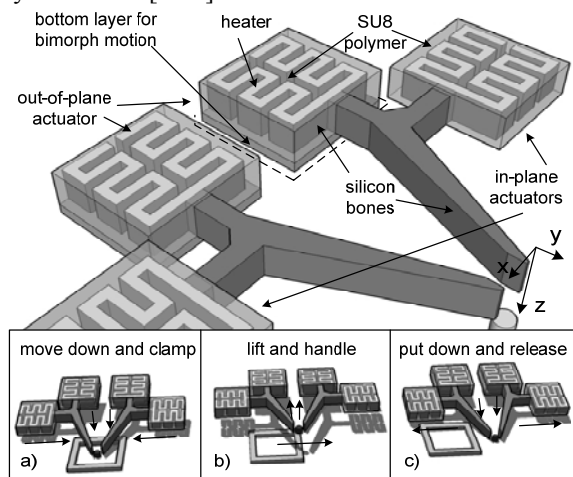


Figure 1. Schematic view of the proposed gripper. The device can a) bend down to clamp an object, b) grasp and move it and c) drop it to the final position.

II. THEORETICAL ANALYSIS

To estimate the performance of the proposed device, and to understand the influence of each device parameter, an analysis based on the laminar model of constraint polymer theory is carried out [4].

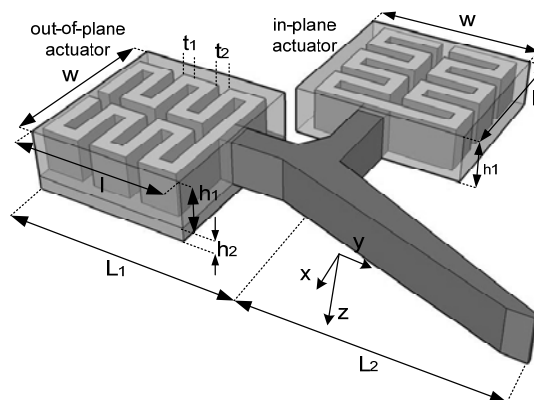


Figure 2. Symbols used in the analytical model of the proposed gripper.

The geometric symbols of a single gripper arm are drawn in Fig.2. The two types of actuators share the same geometry for the silicon-SU8 block.

The performance of the device can be estimated by a mechanical model, which starts from the calculation of the effective mechanical factors of the constraint material block. In this design, the silicon plates used to confine the polymer have the same width as the SU8 layer in between ($t_1=t_2$). Thus, the effective CTE and Young's Modulus of the silicon-SU8 block [4] can be simplified and written as:

$$\alpha_{block} = \frac{\alpha_{SU8} + \alpha_{Si}}{2} + \frac{\nu_{SU8}(\alpha_{SU8} - \alpha_{Si})}{1 - \nu_{SU8} + \eta(1 - \nu_{Si})} \quad (1)$$

$$E_{block} = 2E_{SU8} \sqrt{\left[1 + \eta \frac{2\nu_{SU8}(\nu_{SU8} - \eta\nu_{Si})}{1 - \nu_{SU8} + \eta(1 - \nu_{Si})} \right]} \quad (2)$$

where E , α and ν are Young's Modulus, CTE and Poisson ratio of the material, respectively, while $\eta = E_{SU8}/E_{Si}$ is the ratio of the Young's Modulus of the SU8 and silicon. The displacement can be derived based on the stiffness and motion calculations of the both actuators in different deforming direction. To simplify the calculation, the stiffness values are assumed to be constant.

For the in-plane actuator, the stiffness in three different directions can be written as:

$$k_{in1} = E_{block} w h_1 / l \quad (3)$$

$$k_{in2} = E_{block} w^3 h_1 / 4l \quad (4)$$

$$k_{in3} = E_{block} w h_1^3 / 4l \quad (5)$$

The subscript 1, 2 and 3 represent stiffness in axial direction, lateral bending direction and downward bending direction, respectively. Variables l , w and h_1 are the length, width and thickness of the silicon-SU8 block, respectively.

For the out-of-plane actuator, the stiffness in three directions is:

$$k_{out1} = (E_{block} h_1 + E_{Al} h_2) w / l \quad (5)$$

$$k_{out2} = (E_{block} h_1 + E_{Al} h_2) w^3 / 4l \quad (6)$$

$$k_{out3} = \frac{w h_1 h_2^2 E_{block}}{4l^3 (1 + mn)} \left[4 + 6m + 4m^2 + nm^3 + 1/mn \right] \quad (7)$$

where h_2 is the stiffness of the aluminum layer in the out-of-plane bimorph structure, $m = h_1/h_2$ and $n = E_{block}/E_{Al}$.

The thickness of the silicon-SU8 block is a very important parameter in the gripper design. Fig.3 shows how the thickness of the silicon-SU8 block influences the stiffness of the actuators, which will consequently affect the displacement of the gripper arm.

In the x direction, the motion of the arm is determined by the k_{in1} and k_{out2} . In Fig.3, since k_{in1} is much larger than k_{out2} , the motion in x direction is dominated by the in-plane actuator. The

displacement of the in-plane actuator is not sensitive to the layer thickness, and the output force is proportional to the thickness, when ignoring the influence of the thickness on the constraint effect in the laminar model.

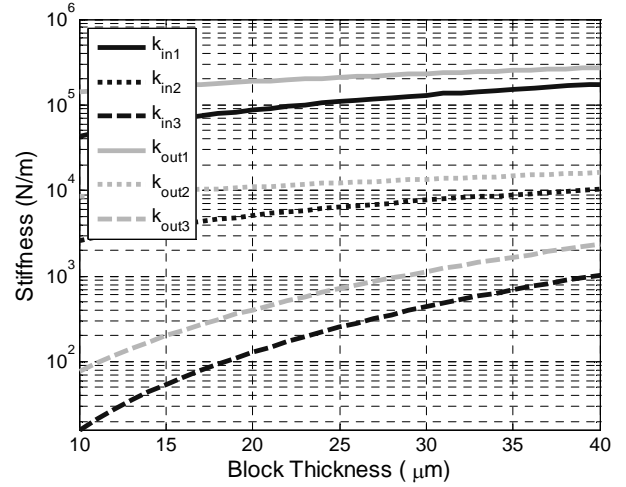


Figure 3. The influence of the silicon-SU8 block thickness on the stiffness of the two types of actuators in all directions.

In the z direction, the motion of the arm is determined by the k_{in3} and k_{out3} . When the block thickness reduces, the ratio between k_{out3} and k_{in3} will increase, due to the existence of the 3 μm aluminum layer under the out-of-plane actuator. This consequently results in a more efficient delivery of the out-of-plane motion for the out-of-plane actuator to the tip of the gripper arm. The displacement of the out-of-plane actuator increases with the reduction of the thickness as well. These, in total, enhance the gripper motion in the z direction.

Assuming a uniform temperature change across the actuators, the displacement of a single gripper tip in the x direction can be written approximately as:

$$\Delta x = \alpha_{block} \Delta T l \frac{k_{in1}}{k_{in1} + k_{out2}} \frac{L_1 + L_2}{L_1} \quad (7)$$

The motion in the z direction can be calculated based on Timoshenko's formulas [3]. To get a similar form as equation (7), the displacement in z direction is written as

$$\Delta z = \alpha_z \Delta T l \frac{k_{out3}}{k_{out3} + k_{in3}} \frac{L_1 + L_2}{L_{act}} \quad (8)$$

$$\alpha_z = \frac{3l(\alpha_{block} - \alpha_{Al})(1 + 1/m)^2}{(h_1 + h_2) \left[3(1 + 1/m)^2 + (1 + 1/mn)(1/m^2 + mn) \right]} \quad (9)$$

where α_z is an effective thermal displacement factor, which is independent of the actuator length and temperature change.

In Table 1 the material properties [4] and geometry parameters used in the design are listed. Fig.4 shows the displacement of the gripper tip per unit temperature change for different block thickness.

TABLE 1. MATERIAL PROPERTIES AND GEOMETRY FACTORS USED IN THE CALCULATION.

Material Properties			
E_{SU8}	3.2 GPa	E_{Si}	130 GPa
α_{SU8}	150.7×10^{-6}	α_{Si}	2.06×10^{-6}
ν_{SU8}	0.33	ν_{Si}	0.28
E_{Al}	69 GPa	α_{Al}	23×10^{-6}
Design Parameters			
w	126 μm	l	260 μm
L_1	350 μm	L_2	380 μm
h_1	20, 30 μm	h_2	3 μm

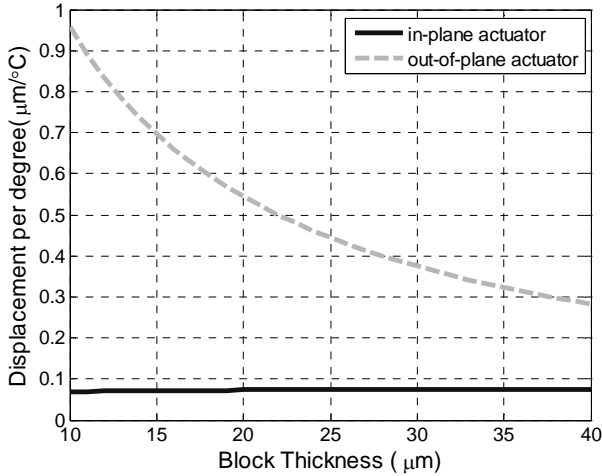


Figure 4. Calculated displacement per unit temperature change as a function of block thickness

The calculation shows a consistent result with the analysis above. For the experimental verification, in order to reach a large motion in the out-of-plane direction, while keeping the polymer being constrained effectively to generate enough in-plane motion and force, the thickness of the layer is chosen to be 20 μm .

III. FEA SIMULATION

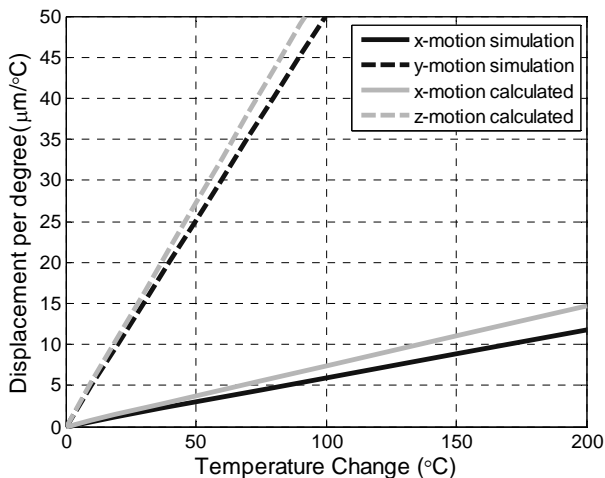


Figure 5. Calculated and simulated displacement in x and z direction with average temperature change

To better understand the behavior of the gripper design and estimate the performance of the device, FEA software (COMSOL) is used to simulate the design.

Fig.5 shows the simulated displacement of the device, with the same situation as in the calculation, where a uniform temperature is applied on each actuator separately. The two methods give similar results.

To mimic the real situation, thermal domain analysis is applied in another simulation, where heat is generated uniformly on the actuator, and transfer to the substrate and other low temperature part of the device. The thermal conduction of the surrounding air is taken into account in the model as well, while the convection is not considered, for reducing the complexity of the simulation.

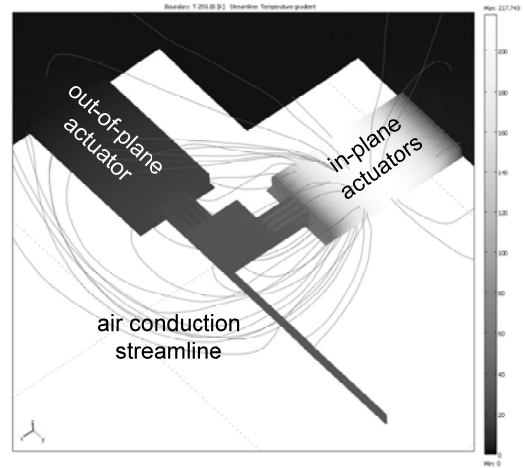


Figure 6. Simulated temperature distribution by activating the in-plane actuator.

Fig.6 shows a simulation result of a single gripper arm, where the in-plane actuator is activated. There are two main differences between the simulation and the analytical model.

First, the temperature distribution is not uniform. The center part of the actuator is much higher than the ends. The average temperature across the actuator is about 60% to 70% of the maximum temperature. This difference causes main discrepancy between the analytical model and the real situation.

Second, thermal cross talk between the two actuators occurs. This results in an unwanted motion of the unactivated actuator. Simulation shows that, when an maximum temperature of 220°C (150°C in average) is reached on the in-plane actuator, the out-of-plane actuator experiences a 20°C average temperature change due to the thermal conduction through the joint point and surrounding air. Since the out-of-plane actuator generates motions more easily than the in-plane actuator (Fig.4), the thermal cross talk consequently generates a 4 μm downward bending motion together with the desired in-plane movement.

IV. MEASUREMENT

Fig.7 shows some picture of the fabricated gripper during the measurement. The gripper arms can perform in-plane clamping motion and out-of-plane bending motion (out of focus) of the bottom arm.

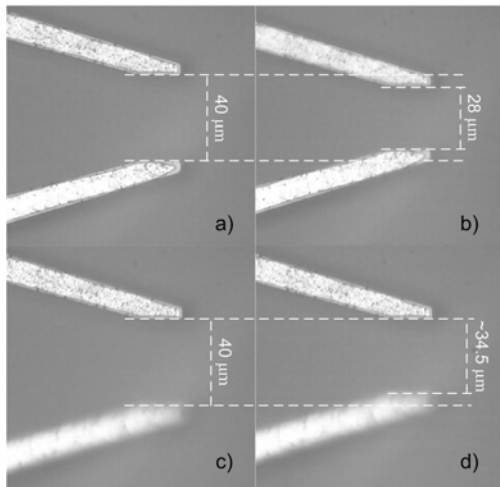


Figure 7. Optical images of the gripper tips during the actuation: a) original position; b) gripper in-plane clamping; c) bottom arm bend down; d) bottom arm bend down and clamp.

Figs. 8 & 9 show the measured displacement on the tip of a single gripper arm versus the applied voltage and average temperature. In the x direction, the maximum displacement is $7.4 \mu\text{m}$ at 1.6 V with 163°C average temperature change (by monitoring the resistance change of the heater). In the z direction, the maximum displacement is $14 \mu\text{m}$ at 2.5 V with 63°C change in average temperature. The power consumption is 26.5 mW for a single in-plane actuator and 87.3 mW for an out-of-plane actuator.

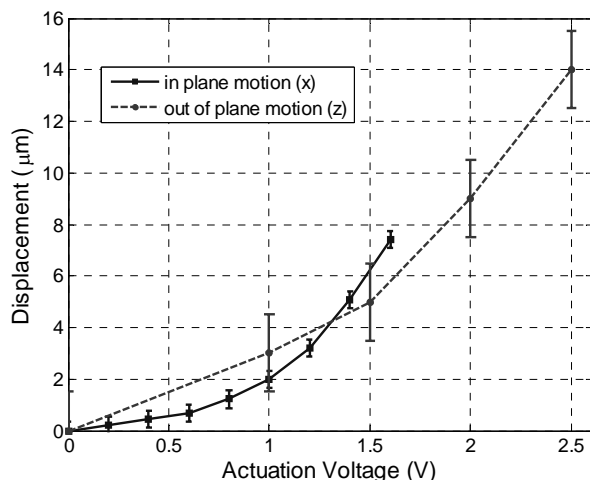


Figure 8. The measured displacement in x and z direction versus the applied voltage.

The calculation results are shown in Fig.9 for comparison. The discrepancy comes partly from the difference between the model assumption and the real situation, and partly from the non-ideal fabrication and material characteristics.

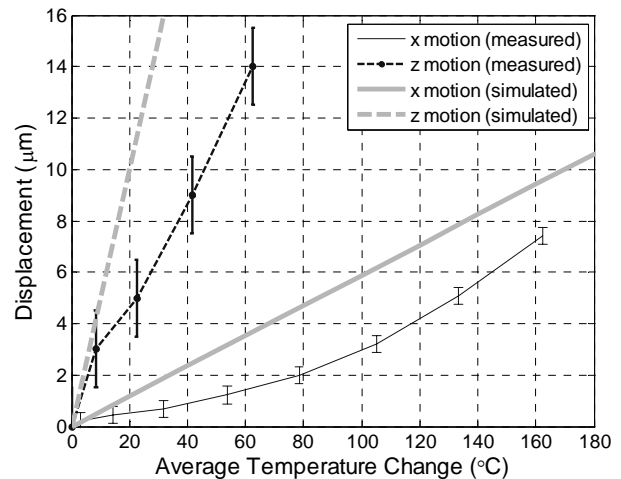


Figure 9. The measured displacement versus the average temperature change on the actuator.

As predicted in the simulation, non-neglectable out-of-plane motions at the tip of the arms are observed with applied voltages larger than 1.6 V , and the corresponding average temperature change is 160°C .

V. CONCLUSION

The presented micro-gripper provides both in-plane clamping and out-of-plane handling capability, with large motions at low voltage and low temperature. An analytical model is developed to estimate the performance of the device. FEA simulation is used to investigate the thermal behavior. Measurement shows that each gripper arm is capable of a $7.4 \mu\text{m}$ in-plane and $14 \mu\text{m}$ out-of-plane motions at 1.6 V and 2.5 V actuation voltage, respectively.

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