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SU-8 Microgrippers based on V-shaped Electrothermal Actuators with Implanted Heaters

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Abstract. This paper presents the design, simulation, fabrication, and characterisation of polymeric microgrippers based on V-shaped electrothermal actuators with two normally operation modes (open and closed) for bio-micromanipulation and micro assembly applications. The microgrippers were simulated using FEM in order to determine the electro-thermo-mechanical behaviour. The microgrippers were fabricated using the SU-8 biocompatible polymer as structural material. The metallic microheaters were embedded in the polymeric structural layers of the microgrippers to improve thermal efficiency and to reduce the undesirable out-of-plane displacement of the gripper. Electro-mechanical testing and characterisation have been performed to determine the openings of the microgripper tips as function of electrical current. For the evaluation of the microgripper displacement, a measurement based on an optical image approach was used. A displacement of 40 m can be obtained for an electrical current of around 25 mA. Over 26 mA the heaters are still working but a softening and a damaging status in the polymer were observed. A comparison between the simulation results and the displacement measurements is presented.

Keywords: microgripper; SU-8; V-shape actuator; FEM simulation.

1 Introduction

Microgrippers as end-effectors are needed tools for handling fragile objects, which can be activated in different ways, by using electrostatic, piezoelectric, thermal actuators, or shape-memory alloys. Microgrippers are important devices in a variety of applications such as micro-robotics, bio micromanipulation (biological cells, blood vessels and tissues) and micro-assembly of Microelectromechanical Systems (MEMS) and MOEMS components (micro lenses, fibres).

The actuators play a significant part of MEMS that are used for energy conversion, motion generation and force production [1]- [4]. The V-shaped actuators are widely used for grippers, micro-valves, micro-pumps and other devices [1]- [6]. V-shaped electrothermal actuators have the advantages of generating a large force (up to several hundred mN), a simple structure design, a lower dive voltage and a large deformation [1]- [6]. Usually, materials as silicon, polysilicon or aluminium are used as the structural material of such actuators.

The electrothermal actuators are based on thermal expansion caused by the Joule effect and offer a simple control, a low driving voltage and a compact structure. Several microgrippers have been studied using the SU-8 based electrothermal actuators designed on different configurations such as, U-shape or V-shape, proving a significant interest in the domain [1]- [24]. SU-8 is a highly-crosslinked epoxy-type photo-patternable polymer which has been used extensively as the preferred polymer material for fabrication of biocompatible structures. The SU-8 polymer has a relatively large coefficient of thermal expansion (CTE) of 52 ppm [16]- [17], good mechanical strength with a modulus of elasticity of 4.02 GPa [17]- [18] and good thermal stability with a glass transition temperature of 210°C [16]- [17] which make it a good polymer material for fabrication of electrothermal actuators. V-shaped thermal actuators are selected for the better underwater performance and the larger force provided [4]- [7].

Different processing technologies were investigated and realized in order to fabricate reliable microgrippers using polymers, such as SU-8 [19] and with reduced out-of-plane displacement [5]- [6], [20]- [24]. Usually two or three material layers are utilized to compose a sandwich structure for the polymeric actuators.

In this paper we present the design, FEM simulation, fabrication and characterization of electrothermal microgrippers based on V-shaped actuators with two operation mode, open and closed. Such microgrippers can be used for bio-micromanipulation and micro assembly applications. The grippers were fabricated using the SU-8 biocompatible polymer as structural material. The metallic microheaters were encapsulated in the polymeric structural layers of the microgrippers to avoid the electrical contact with the manipulated object, to improve thermal efficiency and to reduce the undesirable out-of-plane displacement of the gripper tips. Electro-mechanical characterization has been performed to determine the openings of the microgripper tips as function of electrical current. For the evaluation of the microgripper displacement, a measurement based on an optical image approach was used. A displacement of 40 μm can be obtained for an electrical current of around 25 mA. Over 26 mA the heaters are still working but a softening and a damaging status in the polymer were observed.

2 Design and simulation

Two types of microgrippers were designed using the principle of electrically driven thermal actuation and the V-shaped design in normally open operation mode and in normally closed mode, respectively. For the microgrippers with the normally open operation mode, two initial opening values were designed: 50 μm and, respectively, 100 μm (Figure 1 a)).

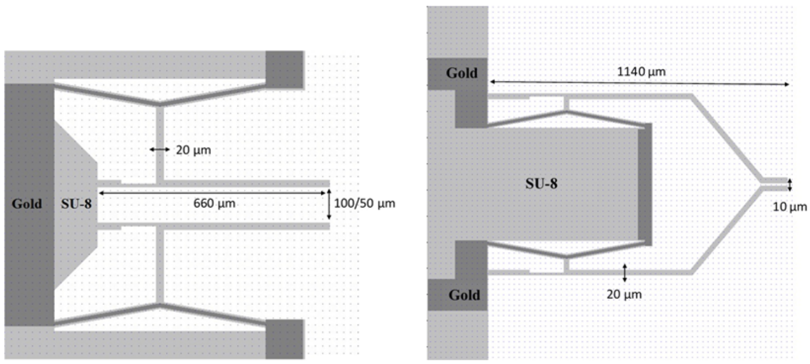
In each design, the micro-heater is embedded between two SU-8 layers. The details of the fabrication work have been reported previously [5]- [6], [20]- [23].

The microgrippers configuration in the normally open operation mode has a total length of 780 μm and different openings (Figure 1 a)). The arms were designed with a width of 20 μm and an initial distance of 100 and 50 μm between the tips. When the gripper is actuated electro-thermally the tips will close and will be able to handle a micro-object.

The microgrippers design in the normally closed operation mode has a total length of 1140 μm and an initial opening of the arms at the tips of 10 μm (Figure 1 b). The polymeric arms were designed with a width of 20 μm. When the gripper is actuated electro-thermally the tips will open and then it can grip a micro-object.

For both proposed configurations, the heater tracks have a width of 10 μm and have been designed to be fabricated using Cr/Au/Cr materials. The optimized configuration consists of three layers, a metal layer (heater) embedded in two SU-8 based structure layers (Figure 2). In both cases the thicknesses of the Cr/Au/Cr films were 30nm/300nm/30nm, and for the two SU-8 layers, each has a thickness of around 10 μm.

In order to check the performance of the microgrippers, finite element simulations were performed. We carried out the coupled electro-thermo-mechanical simulations using the MemMech solver of the Coventorware 2014 software tool. Simplified 3D microgripper models (Figure 2) were meshed using hexahedral elements (Extruded bricks) and the number of the volume elements was optimized using the Split and Merge algorithm.



a) b)

Fig. 1: Designs of the microgrippers: a) V-shaped design in normally open operation mode; b) V-shaped design in normally closed operation mode.

The boundary conditions settings used in simulations are: the initial temperature of the whole structure and the temperature of the environment which were considered to be T_0=27°C, the air convection coefficient which was set to 250 W/m^{2}K. The radiation losses from the device are negligible in comparison with the heat loss by convection to the surrounding media [7], since the maximum temperature reached in the microgripper, in order to operate, is lower than 800°C.

The material property settings Table (1) for the SU-8 polymer were assumed to be: the Poisson's ratio of 0.22, the thermal coefficient of expansion of $5.2 \times 10^{-5}\ K^{-1}$ and the thermal conductivity of SU-8 which is a constant of 2×10^5 pW/μmK. The SU-8 Young's modulus was measured with the nanoindentation technique and was set at 4.6 GPa. The indentation tests have been carried out using A G200 Nano Indenter from Agilent Technologies (Keysight Technologies).

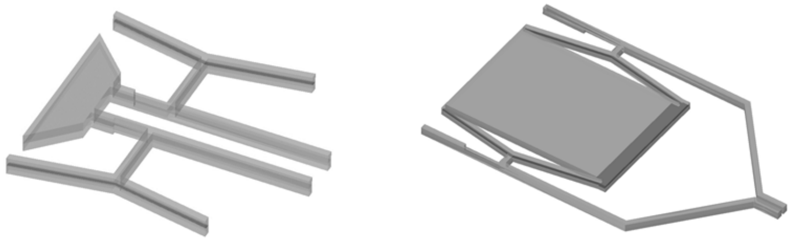
For the gold layer, we used a Young's modulus of 77 GPa, reported for thin films. Regarding the electrical conductivity, we considered the properties reported in [23] for the Cr/Au/Cr films, respectively, a TCR of 0.0014/°C, significantly smaller than the value of 0.0034/°C of the bulk gold material.

Electrical conductivity of the gold layer was set as function of the temperature using the equations (1) and (2):

$$\rho(T) = \rho_0[1 + \varepsilon \cdot (T - T_0)] \tag{1}$$

$$\sigma(T) = \frac{1}{\rho(T)} \tag{2}$$

where $\rho(T)$ is the resistivity as function of the temperature, ρ_0 is the resistivity at T_0 , ε is the TCR of the chromium/gold/chromium layer and σ is the electrical conductivity.



a) b)

Fig. 2: 3D model of the microgrippers with the encapsulated heaters in polymer: a) microgripper in normally open operation mode; b) microgripper in normally closed operation mode (FEM simulations with Coventorware 2014).

Table 1: The materials properties used in simulations

Property	**SU-8**	**Au**
Young's Modulus (E) [Gap]	4.6	77
Poisson ratio (υ)	0.22	0.35
TCE Coefficient of Thermal Expansion (α) [1/K]	$52 \cdot 10^{-6}$	$14.1 \cdot 10^{-6}$ (300K)
Thermal Conductivity (λ) [pW/(μm $\cdot$ K)]	$0.2 \cdot 10^{6}$	$297 \cdot 10^{6}$
Softening point [°C]	210	
Specific Heat [pJ/kgK]	$1.2 \cdot 10^{15}$	$12.87 \cdot 10^{15}$
TCR [/°C]	-	0.0014
Electrical Conductivity [pS/μm]	-	Conf. eq. (1) and (2)
Dielectric Constant	3	-

The simulated values of the temperatures reached in the arms are presented in Figures 3-4 and the simulated in-plane deflections of the tips as function of electrical current in Figure 5.

The simulated out-of-plane deflections of the microgripper tips were presented also in order to evaluate the displacements of the gripper arms (Figure 6). The simulation results demonstrate that the microgripper tips deflect no more than 0.11 μm in the out-of-plane direction (Figure 6). These results demonstrate that the proposed design with equal SU-8 thicknesses disposed in the structures reduce the out-of-plane displacement of the microgrippers arms and optimize the design.

The simulation results indicate that the polymeric microgrippers can work at low operation temperatures of the tips and with large displacements (Figures 4-5). A displacement of 21 μm for each arm was obtained, and a maximum temperature value of 205° C for a current value of 24.28 mA for the microgripper proposed configuration in normally open operation mode. Similar results were obtained for the microgripper designed in normally closed operation mode. At the tips, the maximum temperature is much lower for both designed microgrippers, around 30-35°C.

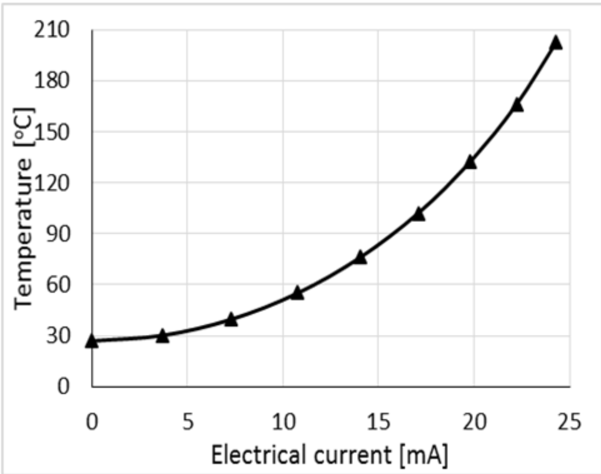
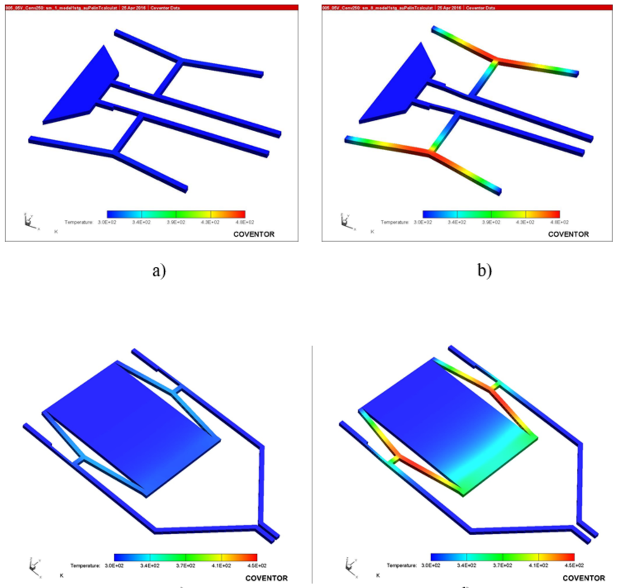
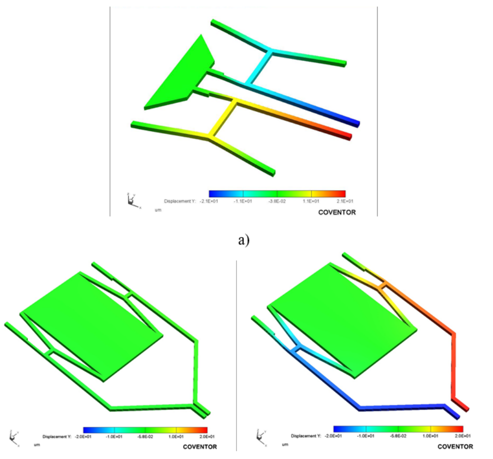


Fig. 3: Simulated temperatures values vs electrical current for the microgripper in normally open operation mode (Coventorware2014 simulation).



a) b) c) d)

Fig. 4: FEM coupled electro-thermo-mechanical simulations results of the temperatures distribution in: a) the microgripper in normally open operation mode at 3.68 mA; b) the microgripper in normally open operation mode at 24.28 mA; c) the microgripper in normally closed operation mode at 3 mA; d) the microgripper in normally closed operation mode at 23 mA; (Coventorware 2014 simulation)



a) b) c)

Fig. 5: FEM coupled electro-thermo-mechanical simulations results of the in-plane deflections for: a) the microgripper in normally open operation mode at 24.28 mA; b) the microgripper in normally closed operation mode at 3 mA; c) the microgripper in normally closed operation mode at 23 mA; (Coventorware 2014 simulation)

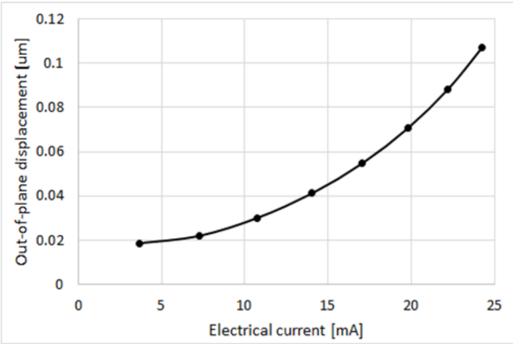


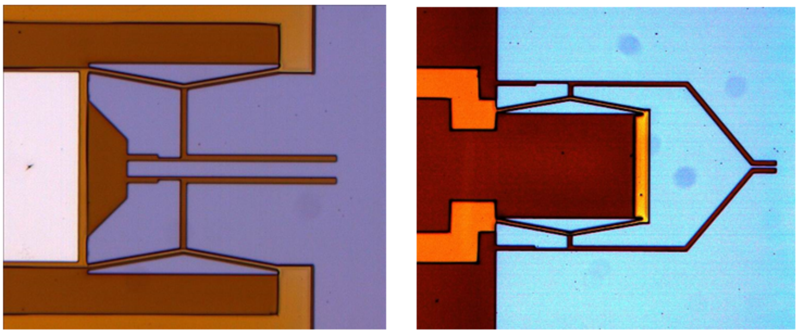
Fig. 6: FEM coupled electro-thermo-mechanical simulations results of the out-of-plane deflections for the microgripper with the normally open operation mode (Coventorware 2014 simulation).

3 Fabrication

For fabrication of the microgripper structures 3 masks were prepared. Two masks were used for the SU-8 configuration in order to obtain the microgripper structures and one mask to achieve the heater lines configurations.

The substrate utilised for the fabrication process was the silicon wafer of any orientation. A standard clean process was realized using the piranha solution and the deionized water. First, a thin layer of Omnicoat was deposited on the silicon wafer by spin-coating at 3000 rpm. The Omnicoat thin layer was thermally treated by baking it at 200°C on a hotplate. Then the SU-8 (MicroChem) polymer was deposited on the wafer by spin-coating in order to obtain a thickness of 10 μm. The wafer was soft-baked at 65°C and at 95°C on a hotplate. The SU-8 layer was then exposed using the first mask. After the exposure, the wafer was post-baked at 65°C and at 95°C on a hotplate and then developed. The polymer structures were hard-baked at 185°C for 30 minutes in order to complete cross-linking of the SU-8 polymer on the wafer.

The metal layer consisting of a sandwich of Cr/Au/Cr films of 30nm/300nm/30nm thicknesses which was evaporated on the prepared wafer. The heater and the pads were obtained using a lift-off process and a thick photoresist. The second SU-8 layer was obtained using the same technological process as for the first layer. In this step, the access to the metallic pads was created using the third mask for SU-8 configuration. The final thermal process of the polymer in this step was the hard-baking for cross-linking of the SU-8 polymer. The final hard-bake was at 195°C for 30 minutes on a hotplate. Figure 7 presents optical images for the fabricated microgripper structures before release. It can be observed that the polymeric microgripper arms and the metallic heater lines have accurate shapes. To release the microgripper structures, the Omnicoat layer was developed and then the wafer was cleaned in the piranha solution. Figure 8 presents a schematic cross section of the microgripper arms where can be observed the metallic layer, placed between the SU-8 layers which encapsulate and isolate then the heater line.



a) b)

Fig. 7: Optical microscope picture of the electrothermal microgrippers: a) the microgripper in normally open operation mode with the initial opening of 50 μm; b) the microgripper in normally closed operation mode;

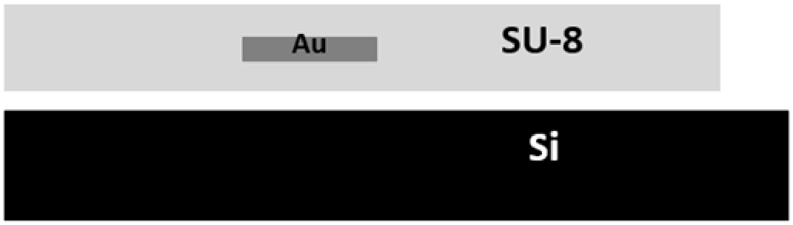


Fig. 8: Schematic cross section of the arms of the microgrippers after fabrication [[6], [23].

4 Characterization and Experimental Tests

For the experimental test the microgrippers array (Figure 9) was divided in individual structures and then the microgrippers pads were fixed one a silicon substrate using a glue or a double scotch. The experiments to validate the model were conducted in air. For characterization of the microgrippers, each structure was fixed manually on a silicon substrate and placed under the microscope. The change in-plane deflection with drive current was observed with a camera with 5 megapixels resolution, and associated viewing software. For each actuation voltage/electrical current the actuated microgripper arms images were captured. The displacement of the gripper tips was measured using then the optical images.

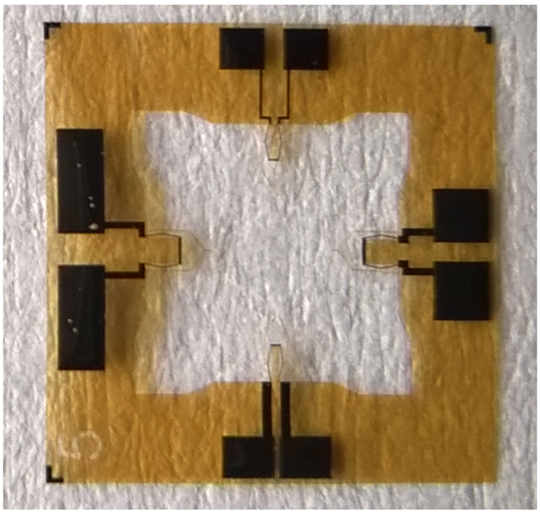


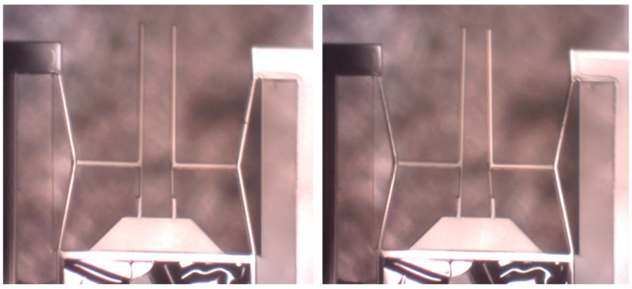
Fig. 9: Optical microscope picture of on chip with four fabricated electrothermal SU-8 microgrippers in normally closed operation mode.

Figure 10 show different stages of the microgrippers when are actuated. We observed that the maximal deflection of the tips is obtained at a current of around 25 mA for the microgripper with open operation mode. When increase the electrical input, the heater temperature would exceed a critical temperature, and SU-8 material softening occurs. Over 25-26 mA the SU-8 microgripper is damaged and the SU-8 material is molten/burned. Figure 10 e) and f) present the tips of the microgripper when in the initial position are open at 50 μm and after actuation the tips are closed.

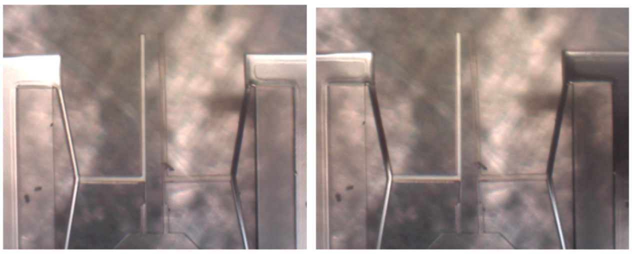
For the microgripper designed in normally closed operation mode the initial opening of the tips is 10 μm. After actuation, the gripper arms can open up to 50 μm. The optical images (Figure 10 g) and h)) show the microgripper polymeric tips when are in the closed position (initial position with 10 μm the opening) and in the open position when the structure is actuated.

Different measurements and tests were performed in order to observe the deflections and the life-cyclic of the SU-8 structures. Deflection vs electrical current data is presented in comparison with simulations results (Figure 11). An error of measurements of ± 3 μm is added in the graphical comparison.

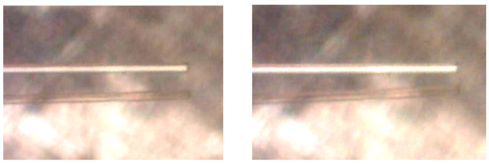
The effect of the very high heater temperature when over 25-26 mA are applied on the microgripper structures is observed in Figure 12 for both microgripper configurations. The microgripper arms are bending downwards due to the damaged actuation V-shape of the structure and the arms could no longer be operated. It can be remarked that the flexible part of the polymeric arms unaffected by the high temperature during actuation remains elastic without fractures of the polymer.



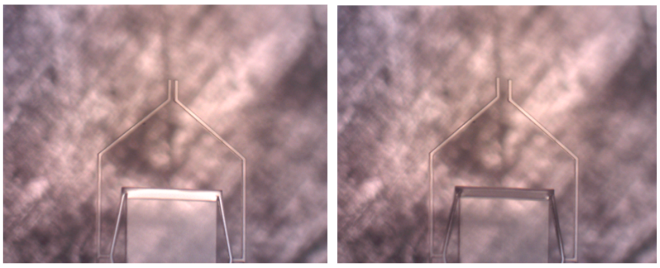
a) open at 0 mA b) close at 22 mA



c) open at 0 mA d) close at 22 mA



e) open f) close



g) close h) open

Fig. 10: Optical images of the actuated microgrippers and the tips in the open and close mode position: a) and b) for the 100 m initial opening; c), d), e), f) for the 50 m initial opening; g) and h) for the microgripper in closed operation mode with 10 m initial opening.

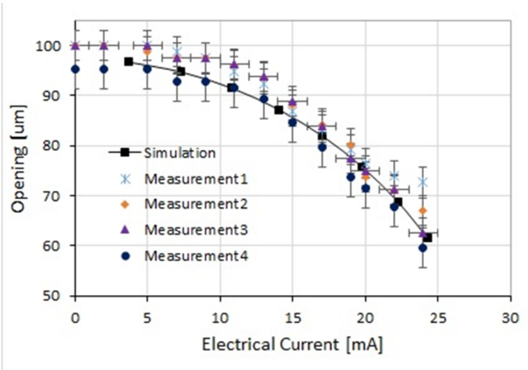
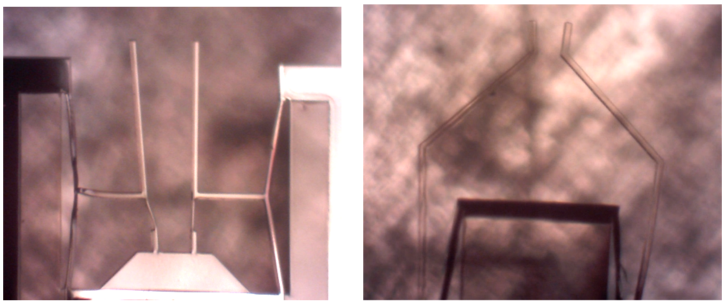


Fig. 11: Displacement measured results of the microgripper in normally open operation mode as a function of electrical current with the error bars vs FEM simulation results.



a) b)

Fig. 12: Optical images of the damaged SU-8 microgrippers: a) microgripper in normally open operation mode; b) microgripper in normally closed operation mode.

5 Conclusions

In this paper, the design, numerical simulations, fabrication, experimental testing and characterization of two type designed V-shaped electro-thermally driven microgrippers were presented. The microgrippers were designed using the principle of electrically driven thermal actuation and the V-shaped configurations. Two normally operation mode was selected: the normally open operation mode and the normally closed operation mode.

The proposed designs were evaluated using the finite element simulations. Coupled electro-thermo-mechanical simulations were performed in order to analyse the microgrippers behaviour in air.

The fabrication steps were also presented. A three photomasks process was used. The biocompatible polymer SU-8 was selected as structural material. The metallic layer that compose the heater line was embedded between two SU-8 layers with the same thickness in order to isolate the conductive part, to improve the thermal efficiency of the structure and to reduce the out-of-plane displacement in the microgrippers.

The characterization and the experimental tests are described also in the paper. The optical microscope images were used to perform the measurements of the gripper tips displacements and the measurements values where compared with the FEM simulations. The gripper opening displacements were measured and the results are presented with respect to the actuation electrical current.

The results of computer simulations and the measurements show an electrical current up to 25 mA for operation and a large displacement of 40-42 μm for the tips, while the maximal temperature rise up near 200°C. on the hottest part of the microgripper. The temperature of the tips remains considerably low, around 30-35°C. The out-of-plane displacement was not observed during the experimental tests while the simulation results gave an out-of-plane displacement less than 0.11 μm.

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