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Chapter 2

An SU-8 Microgripper Based on the Cascaded V-Shaped Electrothermal Actuators: Design, Fabrication, Simulation and Experimental Investigations

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Additional information is available at the end of the chapter

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Abstract

This chapter presents the design, fabrication, numerical simulations and experimental investigations of a polymeric microgripper designed using the cascaded V-shaped electrothermal actuators. The microgripper has a total length around 1 mm and a total thickness of only 20 μm. The microgripper was simulated using electro-thermo-mechanical finite element method (FEM) in order to check the performance of the gripper. As structural material of the microgripper, the SU-8 biocompatible polymer was used during the fabrication process. A fabrication process was implemented to realize the microgripper using a symmetrically sandwich structure. The metallic micro-heaters were encapsulated in the polymeric actuation structure of the microgrippers to reduce the undesirable out-of-plane displacement of the gripper tips and the mechanical stress, to improve the thermal efficiency, and for obtaining the electrical isolation of the structure. Experimental testing has been performed to determine the openings and the temperatures of the microgripper tips as function of electrical current. A displacement of the tips of more than 50 μm can be obtained at an electrical current of around 26–28 mA. A comparison between the simulation results and the measurements were also presented.

Keywords: actuator, electro-thermal, microgripper, SU-8, simulation, polymer

1. Introduction

Microgrippers used as end-effectors are essential tools for holding and manipulating fragile objects. A variety of applications for the microgripper structures was reported. These tools are suitable for handling, positioning, pick and place and biological micro-manipulations such as

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cells, blood vessels and tissues, for applications in micro-assembly of Microelectromechanical Systems (MEMS) and MOEMS components (lenses, fibers) and in micro-robotics.

Different actuators were investigated due to the significant role in the MEMS configuration. The actuation methods include mainly the electrostatic, electromagnetic, piezoelectric and electrothermal principles. Each actuation approaches have their proper disadvantages and benefits in agreement with the designed purpose. The actuators are usually integrated with MEMS for the necessary need of energy conversion, motion generation and force production [1–3]. The V-shaped actuators are widely used for grippers, micro-valves, micro-pumps and other devices. V-shaped electrothermal actuators have the advantages of generating a large force (up to several 100 mN), the simple structure design, a lower dive voltage and a large deformation. Que et al. [2] developed single and cascaded V-shaped electrothermal actuators and present the experimental results. Shen and Chen [3] present an analytical model for cascaded V-shaped actuators bringing a complete description of the mechanical performance. Usually, materials such as silicon, polysilicon or aluminum are used as the structural material of such actuators.

A variety of microgrippers have been studied using the SU-8 based electrothermal actuators designed on different configurations such as, U-shape or V-shape. This is proving the interest in the bio-micro-manipulation domain [1, 4–23]. 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, good mechanical strength with a modulus of elasticity of around 4.02 GPa and good thermal stability with a glass transition temperature of 210°C [15], which make it a good polymer material for fabrication of electrothermal actuators. The polymer V-shaped actuators are preferred for the better performance in aqueous medium [4].

Different processing technologies were investigated and realized in order to fabricate reliable microgripper with reduces out-of-plane displacement [17–22]. Usually two or three material layers are utilized to compose a sandwich structure.

In this chapter, we report a complete work regarding the design, numerical simulation results, fabrication process and the experimental investigations of an SU-8 polymeric microgripper. The design is based on the cascaded V-shaped electrothermal actuators. The SU-8 microgripper can be used for micro-robotics and bio-manipulation and assembly applications. The microgripper was numerically investigated using the coupled electro-thermo-mechanical simulations based on finite element method (FEM) and using the Coventorware 2014 software in order to confirm the performance of the microgripper. To fabricate the microgripper, a sandwich structure actuator with three layers was used. Two kings of fabrication processes were presented in order to improve the structure functionality. As structural material of the microgripper, the SU-8 biocompatible polymer was used during the fabrication process. The metallic micro-heaters were encapsulated in the polymeric actuation structures of the microgrippers to reduce the undesirable out-of-plane displacement of the gripper tips, the mechanical stress and to improve the thermal efficiency and the electrical isolation of the structure. Experimental testing and characterizations have been performed to determine the openings and the temperatures of the microgripper tips as function of electrical current. A comparison between the simulation results and the measurements were also presented.

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2. Design

The SU-8 microgripper was designed in a previous work using the principle of the cascaded V-shaped electrothermal actuators [22]. The gripper was designed with two initial opening of 50 μm and 100 μm, respectively (**Figure 1**). When the gripper structure is electro-thermally actuated the arms and the jaws will close and will be able to handgrip a micro-object. The total length of the gripper arms used to grasp an object is of 920 μm. The arms were designed with a width of 20 μm [22]. A metallic micro-heater is implanted between two SU-8 layers. The heater lines have a width of 10 μm and were designed first, to be fabricated using Cr/Au/Cr materials and second, to be fabricated using only the gold. Usually, a chromium thin layer or other adhesion layers are used to improve the connection between the gold metal and the polymer. On the other hand, it was reported that the deposition of the SU-8 polymer over the gold metal do not need an adhesion layer [23].

The optimized design consists of symmetrically disposed of three material layers. A metallic layer for the heater is implanted between two SU-8 based structure layers having the same thickness, as described previously [18–22]. The thicknesses of the Cr/Au/Cr films were 10 nm/300 nm/10 nm. The thickness of the gold layer is 100–300 nm. For each SU-8 layer we obtained a thickness of 9 μm. The details of the fabrication process where using the Cr/Au/Cr films have been reported also previously in [21] and when using only gold in [24] but for other gripper designs.

The proposed microgripper in this work was designed symmetrically with encapsulated metallic micro-heaters in the structural material of the grippers, the SU-8 polymer, in order to reduce the undesirable out-of-plane displacement of the gripper, to obtain the electrical isolation of the heaters and to reduce the mechanical stress that can occur in the structure [22].

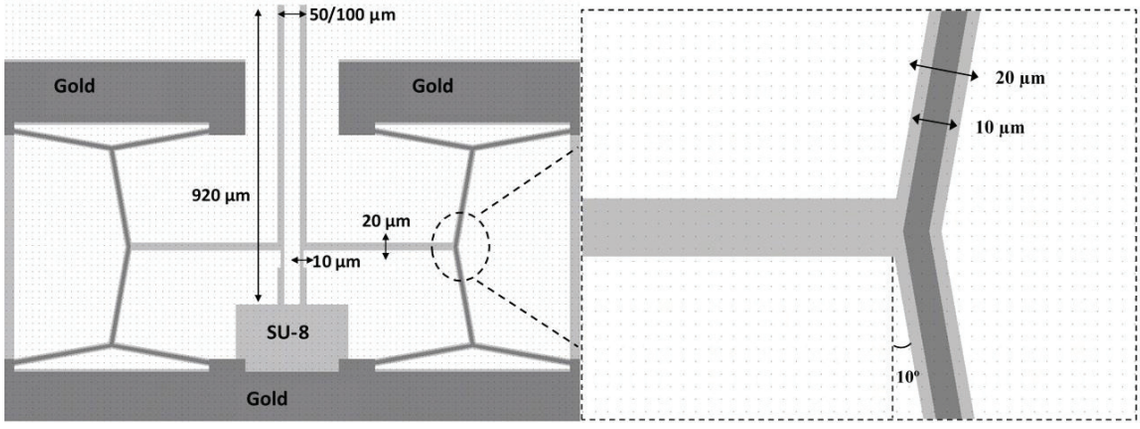


Figure 1. Schematic design of the SU-8 microgripper [22].

3. Finite element simulation

In order to check the performance of the microgripper, finite element simulations were performed. The microgripper with the initial opening of 50 μm was numerically investigated.

Coupled electro-thermo-mechanical simulations were completed using the MemMech simulator from the Coventorware 2014 software tool. A simplified 3D microgripper model (**Figure 2**) was meshed using hexahedral elements (Extruded bricks). The number of volume elements was optimized choosing the proper size of the mesh elements using the Split and Merge algorithm. The thicknesses of the SU-8 layers and the gold layer are 18 μm and 300 nm, respectively.

The materials properties and the surface boundary conditions were set for the simulations (**Table 1**). The initial temperature of the whole structure and the temperature of the environment were considered to be $T_0 = 27°C$, with respect to the Coventorware settings requirements for such kind of analyses. The radiation losses from the device are negligible in comparison with the heat loss by convection to the surrounding media [4], since the maximum temperature reached in the microgripper, in order to operate, is lower than 800°C. The air convection coefficient was set to 250 W/m^2 K [4].

The Young's modulus of the SU-8 was measured with the nanoindentation technique and was set in simulations for a value of 4.6 GPa (**Figure 3**). The indentation tests have been carried out using A G200 Nano Indenter from Agilent Technologies (Keysight Technologies).

The thermal coefficient of expansion was fixed at 52 (ppm/°C) and the thermal conductivity at 2 X 10^5 pW/μmK. For the gold layer we used a Young's modulus of 77 GPa reported for thin films.

The TCR, temperature coefficient of resistance, was measured for the Cr/Au/Cr thin films and obtained the value 0.001569/°C. This value is significantly smaller than the value of 0.0034–0.0037/°C used for the bulk gold material. For the thin gold film the TCR was measured at 0.00314/°C.

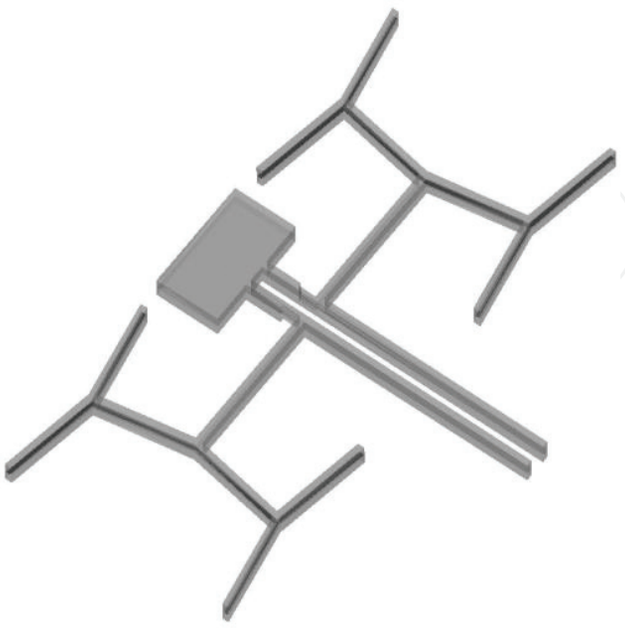


Figure 2. The simplified 3D model of the microgripper with encapsulated heaters in SU-8 polymer: The layers sandwich structure used in FEM simulations (Coventorware 2014) [22].

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Property	SU-8	Au
Young's Modulus (E) [GPa]	4.6	77
Poisson ratio (ν)	0.22	0.35
TCE Coeff. of Thermal Expansion (α) [1/K]	52×10^{-6}	14.1×10^{-6} (300 K)
Thermal Conductivity (λ) [pW/(μm·K)]	0.2×10^{6}	297×10^{6}
Softening point [°C]	210	
SpecificHeat(pJ/kgK)	1.2×10^{15}	12.87×10^{15}
TCR [/°C]	—	0.001569
Electric Cond. [pS/μm]		Conf. Eq. (1) and (2)

Table 1. The materials properties used in simulations.

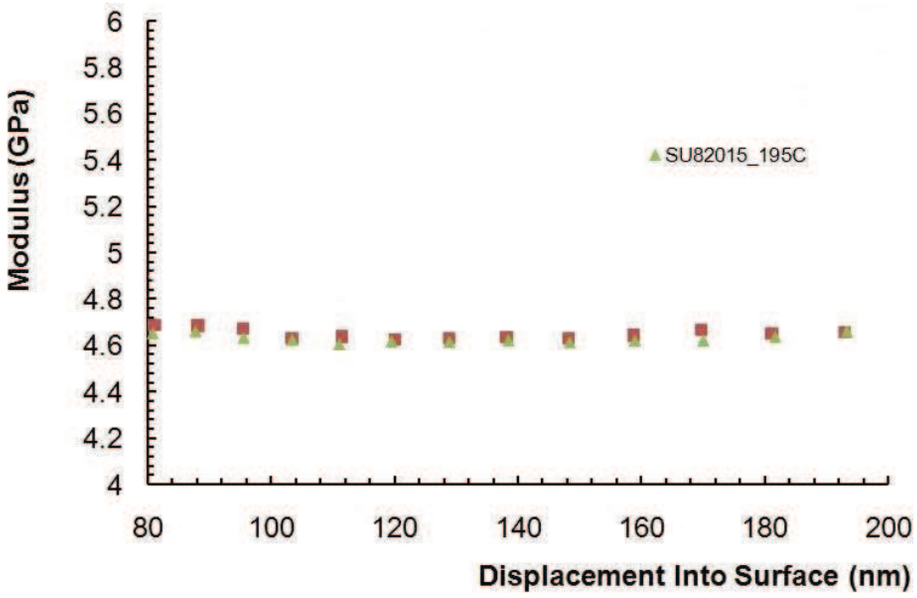


Figure 3. Young's modulus vs displacement into surface of SU-8 layer.

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

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

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

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 gold and σ is the electrical conductivity.

The simulation results regarding the temperatures distribution reached in the microgripper when it is actuated were visually compared with the thermal measurements realized using an IR camera SC5000 from FLIR system (**Figure 4**). The thermal measurements show that the distribution of the temperatures in the microgripper has a similar map with the simulation results. The temperature values at the tips remains near initial temperature of the environment.

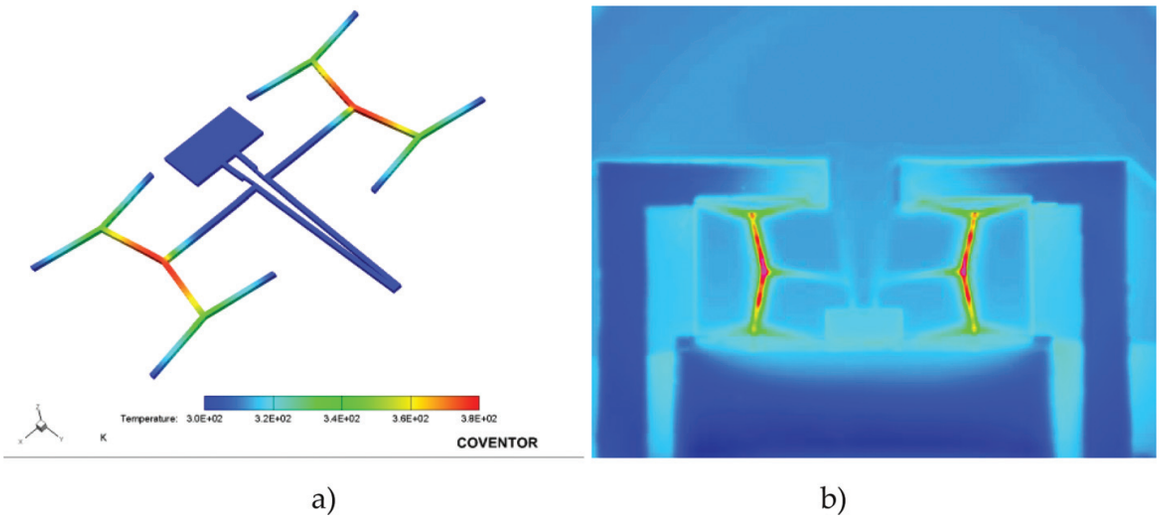


Figure 4. Simulations and thermal measurements results: (a) FEM coupled electro-thermo-mechanical simulations results of the temperatures distribution in the microgripper at 22 mA (Coventorware 2014 simulation) [22]; (b) the radiation distribution in the microgripper (IR thermography measurements).

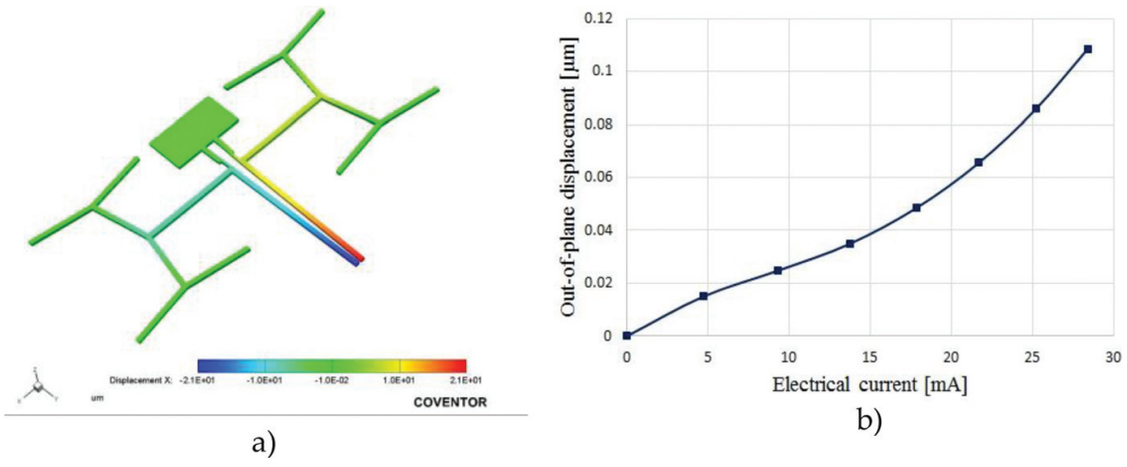


Figure 5. FEM coupled electro-thermo-mechanical simulations results: (a) the in-plane deflections at 22 mA [22]; (b) the out-of-plane displacements of the tips vs. electrical current (Coventorware 2014 simulation).

The simulated in-plane and the out-of-plane deflections of the microgripper tips were presented in order to evaluate the opening and the displacements of the gripper arms (**Figure 5**). The simulation results demonstrate that the tips deflect no more than 0.12 µm in the out-of-plane direction (**Figure 5(b)**).

The simulation results show that the gripper can work up to a temperature of 165°C for a complete closing tips. The gripper can continue to work up to 205°C in order to obtain a higher displacement or a higher pressure on the griped micro-object. The results indicate that the polymeric micromanipulators can work at low operation temperatures of the tips and with high in plane displacement. A displacement of 25 µm for each microgripper polymeric arm was obtained at a temperature value of 165°C and for a current value of 25 mA. At the tips the temperatures remain of 30–35°C close to the settings performed for the initial temperature of the media. The capable manipulating size range of the simulated microgripper is from 1 to 50 µm. If

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we consider the microgripper with 100 μm the initial opening then the manipulating size is from 50 to 90 μm. A temperature change with only 5°C is observed at the microgripper tips.

4. Fabrication and characterization

The fabrication of the microgrippers is based on a three mask process. The OmniCoat stripper (MicroChem) is used in order to completely release the final structures [21–24].

4.1. First fabrication process

A silicon wafer of any orientation was used after a typical chemical cleaning. A thin layer of 40 nm thickness of Omnicoat was deposited on the silicon wafer by spin-coating and baked at 200°C on a hotplate for 1 minute. Then the SU-8 2015 (MicroChem) polymer was deposited on the wafer using a spinner at 4000 rpm in order to obtain a thickness of 9 μm. The wafer was soft-baked at 65°C and at 95°C for 1 minute and 3 minutes, respectively. The SU-8 layer was then patterned using the first mask in order to obtain the microgripper configuration. After the exposure, the wafer was post-baked at 65°C and at 95°C for 1 minute and 2 minutes, respectively and then developed using mr-Dev 600 developer. The polymer structure was hard-baked at 185°C for 15 minutes in order to complete cross-linking of the SU-8 polymer. The metal layer consists of a sandwich of Cr/Au/Cr films of 10 nm/300 nm/10 nm thicknesses. The metals were evaporated and the heater and pads were obtained using a lift-off process based on AZ4562 photoresist. The second SU-8 2015 layer was obtained using the same settings as for the first layer. In this step the access to the metallic pads was created using the third mask for SU-8. The final thermal process of the polymer in this step was the hard-baking at 195°C for 30 minutes for cross-linking of the SU-8 polymer. To release the microgripper structures the Omnicoat layer was developed (**Figure 6**). The SU-8 and the metallic layers are well patterned (**Figure 7**). **Figure 8** (a) shows an optical picture of the fabricated microgripper before releasing.

4.2. Second fabrication process

A thin layer of Omnicoat was deposited on a silicon wafer by spin-coating as in the first fabrication process. The SU-8 polymer was deposited on the wafer using a spinner in order to

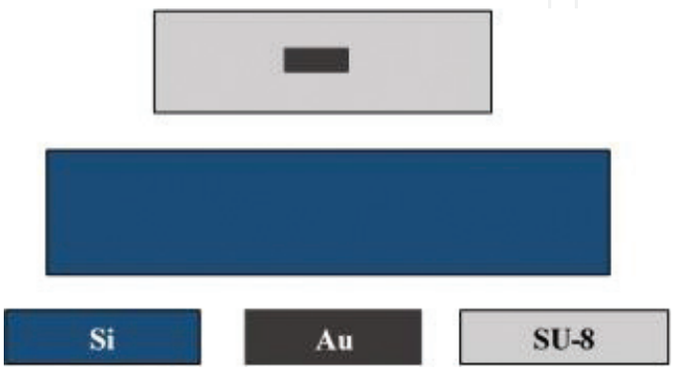


Figure 6. Schematic cross section of the actuator arm after fabrication and release.

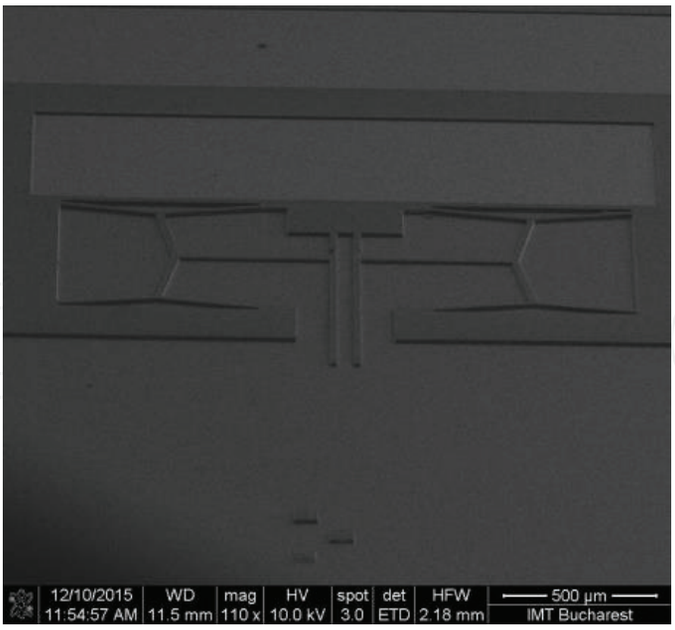


Figure 7. SEM image of the fabricated microgripper using the Cr/au/Cr films for the heater.

obtain a thickness of ~10 μm. The wafer was soft-baked in the same conditions and the SU-8 layer was then exposed using the first mask. After the exposure, the wafer was post-baked and then developed. The polymer structure was hard-baked in order to complete cross-linking of the SU-8 polymer. The heaters and the pads were obtained using a lift-off process based on AZ4562 photoresist. An O_2 plasma treatment was performed for a couple of seconds in order to clean and increase the adhesion of the substrate [24]. Then, a metal layer of a gold thin film with 300 nm thickness was evaporated on the wafer. The second SU-8 layer was obtained using the same conditions as for the first layer. In this step the access to the metallic pads was created using the third mask for SU-8. The final thermal process of the polymer in this step was the hard-baking at 195°C for 30 minutes for cross-linking of the SU-8 polymer. To release the microgripper structures the Omnicoat layer was developed. **Figure 8** (b) shows an optical picture of the released fabricated microgripper. A released chip with 4 structures is presented in **Figure 8** (c).

5. Experimental testing

In order to validate the model, the experiments were performed in air. For the tests we used the microgrippers with 50 μm the initial opening. Each structure was fixed manually on a silicon substrate (**Figure 9**) and the electrical contacts were placed directly on the metallic pads.

The dimensions of the microheaters were measured using a miscroscope. The TCR (temperature coefficient of resistance) measurements were carried out using a small chamber where the microgripper were fixed one a hotplate [21, 25]. A thermocouple based temperature sensor was used. Then, the heater resistance was measured at different temperatures. Based on the

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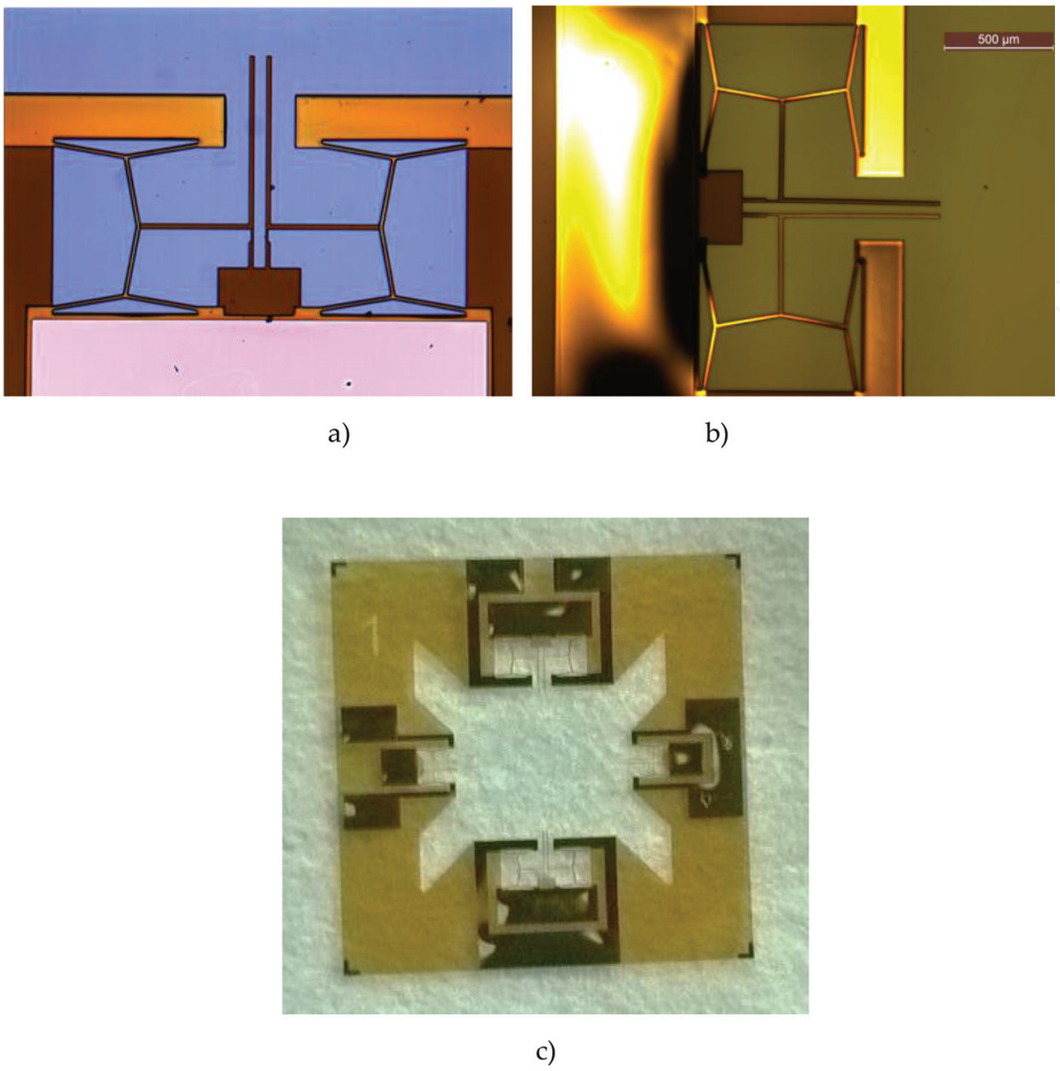


Figure 8. Optical microscope picture of the fabricated electrothermal SU-8 microgripper: (a) the microgripper with Cr/au/Cr films [22]; (b) the fabricated microgripper using the gold film for the heater; (c) a released chip with 4 structures with au film used for the heater.

values of the line equation parameters which fit the resistance graphs, the TCR was determined for each microgripper. For the Cr/Au/Cr thin films microgrippers the measured TCR is 0.001569/°C. For the thin gold film microgripper the TCR was found to be 0.00314/°C using the same microgripper configuration. We notice that for the gold microgripper the measured TCR value is very close to the bulk gold values which are between 0.0034 and 0.0037/°C, while for the Cr/Au/Cr thin films microgrippers the measured TCR is half of the bulk value.

These measured TCR values were used to determine the heater temperatures when the microgripper is actuated.

The in-plane deflection change with drive current was observed with an optical microscope and a camera with the associated viewing software. For each actuation step, the displacements of the gripper tips were measured using the optical images. **Figure 10** shows the first and the last stage of the opening-closing tips of the microgripper, while the **Figure 11** proves a good

agreement between the simulation results and the measured openings and the temperatures of the microgripper arms. The out-of-plane displacement was not observed in the experiments while the simulation results provided an out-of-plane displacement less than 100 nm. Currents larger than 27–28 mA make the SU-8 softer and the device will be damaged due to the increased temperature over 210°C.

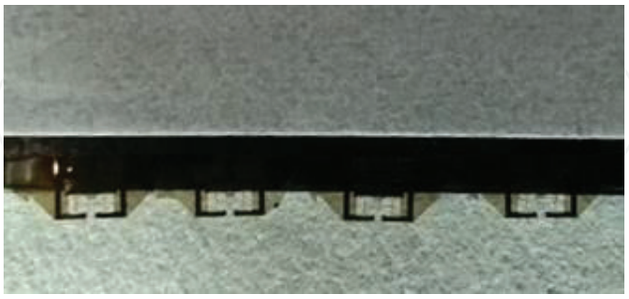


Figure 9. The fixed structures on a silicon substrate for experiments tests.

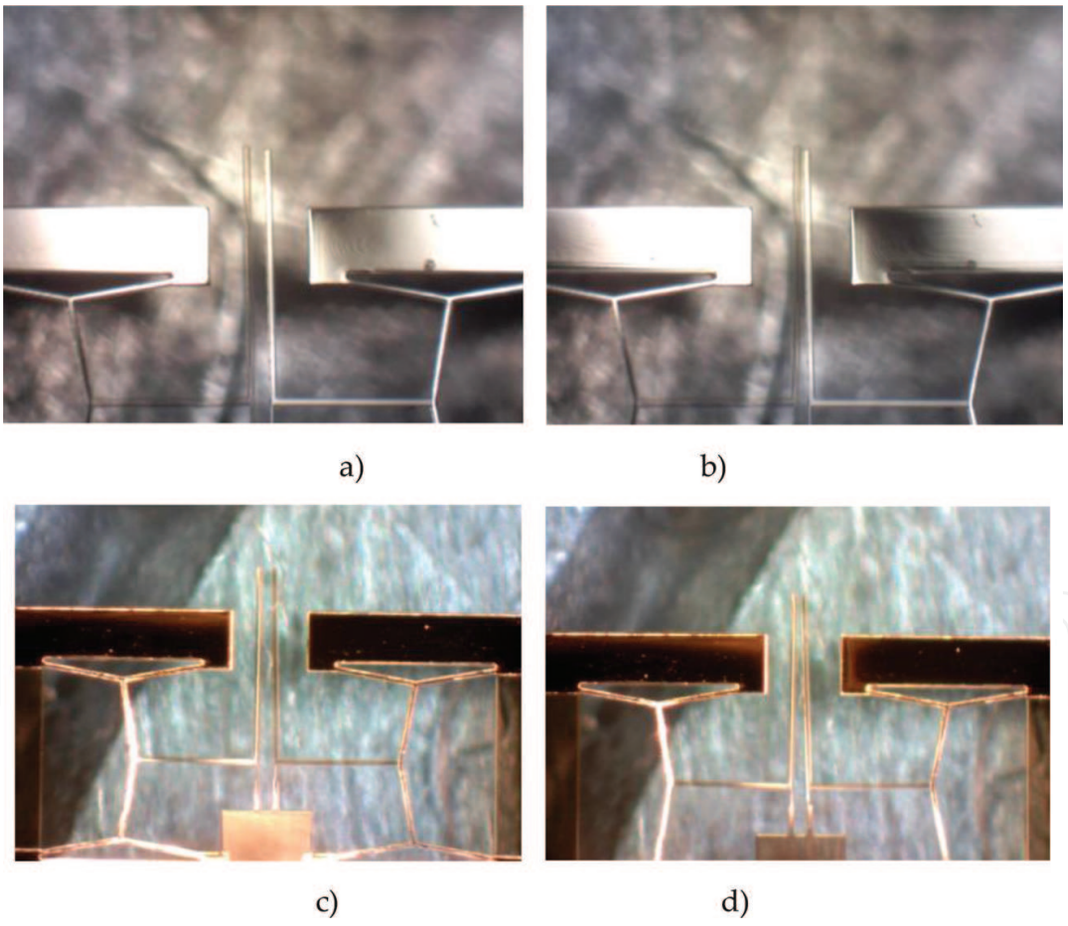


Figure 10. Optical images of the actuated microgrippers with the tips in the open and close stage: (a) the initial stage of the microgripper tips with Cr/au/Cr films used for the heater and with the initial opening of 50 μm [22]; (b) closing tips stage at 24 mA for the microgripper with Cr/au/Cr films used for the heater [22]; (c) the initial stage of the microgripper tips with au film used for the heater and with the initial opening of 50 μm; (b) closing tips stage at 24 mA for the microgripper with au film used for the heater;

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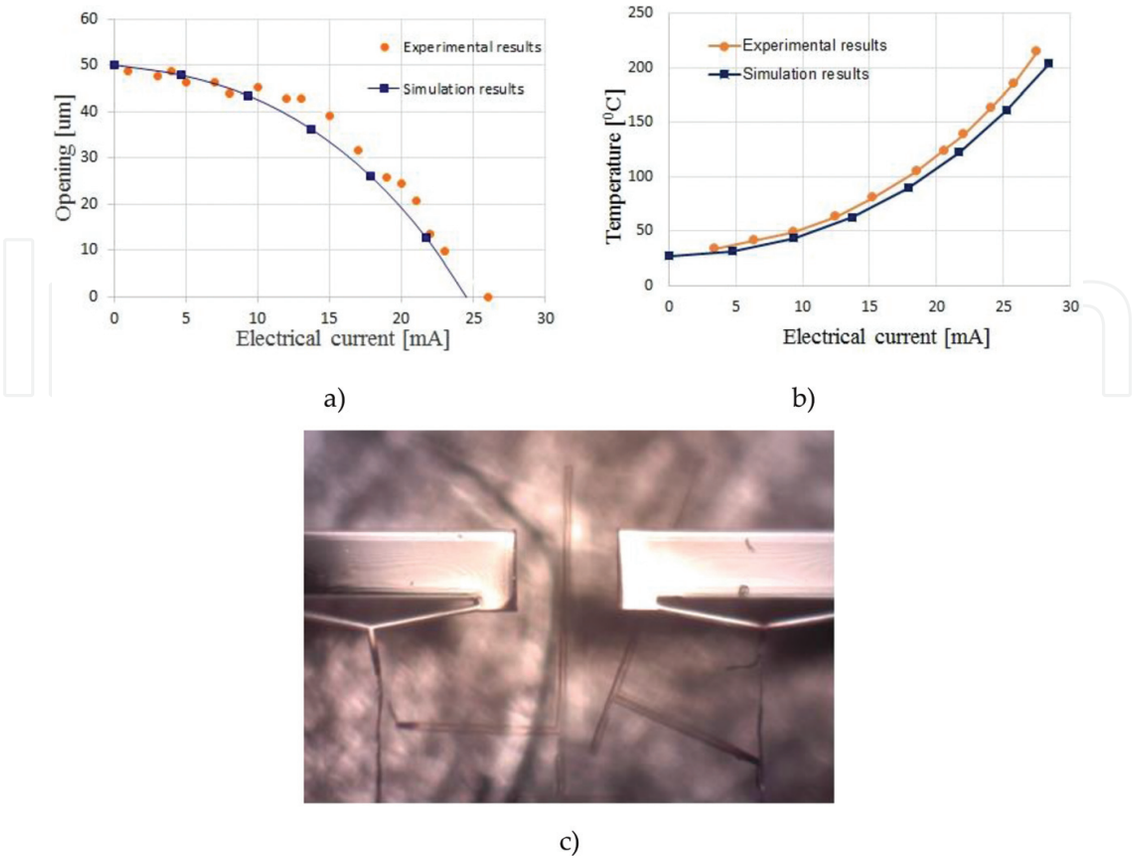


Figure 11. Experimental and simulation results: (a) measurements and simulation results of the jaw displacement versus electrical current; (b) measurements and simulation results of the maximal values of the temperatures in the microgripper versus electrical current; (c) optical image of the damaged SU-8 microgripper at 28 mA [22].

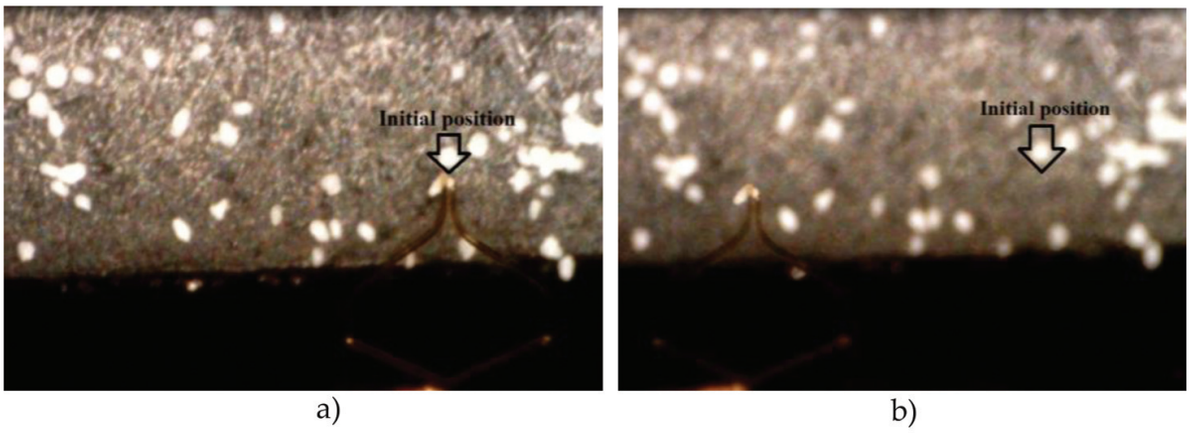


Figure 12. Optical images of an SU-8 microgripper manipulating a polymeric micro-object: (a) gripping the object; (b) placing the object in the final position.

In order to demonstrate the microgripper capability, different micro-elements were used in order to pick and place and manipulate them with the gripper arms of a similar SU-8 fabricated microgripper (**Figure 12**).

6. Conclusions

In this paper, a complete work regarding an SU-8 electro thermally actuated microgripper based one a cascaded V-shaped configuration was presented. The gripper were designed, fabricated and investigated experimentally and numerically. Two kind of fabrication were presented, using only a gold thin layer for the heater avoiding the deposition of an adhesion metal, like chromium and using Cr/Au/Cr films for the heaters. The optimized design consists of three material layers symmetrically disposed. The metallic layer for the heater is implanted between two SU-8 based structure layers with the same thickness. From numerical simulation, the out-of-plane displacement of the tips was found to be always lower than 100 nm during the operation process.

Therefore, the fabrication processes can be used in the fabrication of different SU-8 based MEMS devices actuated electrothermally with the in-plane deflection.

The results show that the microgripper can work in air in his maximal stage for an electrical current up to 25–26 mA and a temperature up to 165°C. A 50 μm jaw gap can be obtained for 24–25 mA. The temperature of the microgripper SU-8 tip remains below 35°C. Our experimental and the simulation results demonstrate that our microgripper fulfills the design requirements having a thickness of less than 20 μm and the out-of-plane displacement almost eliminated.

A comparison between the simulations results and the measurements was presented regarding the displacements/opening of the arms and the maximal temperatures reached in the structure. The simulation results are in good agreement with the measurements.

Over 26–28 mA the device is damaged due to the SU-8 transformations over the glass transition temperature reached in the structure.

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