Measurement and Characterisation of Displacement and Temperature of Polymer Based Electrothermal Microgrippers

Muaiyd Al-Zani[1], Changhai Wang[1], Rodica Voicu[2], Raluca Muller[2]

Abstract: This paper presents our work on measurement and characterization of electrothermal microgrippers for micromanipulation and microassembly applications. The SU-8 based microgrippers were designed with embedded microheaters in the actuation structures of the grippers to improve thermal efficiency and to reduce the undesirable out of plane movement of the gripper tips. Electrothermal testing and characterization have been conducted to determine the displacement between the grippers' tips under an applied voltage. A measurement method based on an image tracking approach was used to measure gripper displacement. It has been shown that a displacement of 11 µm and 8 µm can be obtained at the actuation voltage of 0.65 V and 0.7 V for two different designs. The microheaters were also used as a sensor to find out the heater temperature. This has been done by measuring the resistance change at the applied voltage. The temperature coefficient of resistance (TCR) was determined independently and then used to calculate the heater temperature based on the measured resistance change. The values of TCR of the thin film chromium/gold microheaters were determined to be 0.00136/°C and 0.00149/°C at 20°C for the two different gripper designs which are significantly less than the value of the bulk gold material which is 0.0034/°C. The results show that it is important to determine the TCR of the thin film microheaters for accurate calculation of the heater temperature at an applied actuation voltage. In addition, the resistivity of the metal layer has been calculated and it was between 6.2 µΩ·cm and 6.8 µΩ·cm. this value is much larger than 2.44 µΩ·cm for the bulk gold value. For the fabricated thin gold film based microheaters, it was found the ratio of the increase in the resistivity is the same as the ratio of decrease in the TCR value.

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1. Introduction

Microgrippers have been of significant interest for micromanipulation and microassembly applications and several griper designs have been studied previously (Lopez-Walle et al., 2008; Biganzoli & Fantoni, 2008; Gonzalez and Lumia, 2015; Kyung et al., 2008). Polymer based electrothermal microgrippers offer advantages of low cost and ease of fabrication over the other types of grippers. SU-8 is an epoxy polymer which has been used extensively as the preferred polymer material for fabrication of electrothermal microgrippers and other polymer based MEMS (Chu et al., 2011). The SU-8 polymer has a large coefficient of thermal expansion (CTE) of 52 ppm (MicroChem/a, n.d.), good mechanical strength with a modulus of elasticity of 4.02 GPa (Lorenz et al., 1997) and wide range of thermal stability with a glass transition temperature (Tg) of more than 200°C (Li et al., 2014) which make it a good polymer material for fabrication of electrothermal actuators such as microgrippers. Testing and characterization of gripper performance is an essential process in development of microgrippers. The most important parameters to study are the displacement of the grippers, the heater temperature and the maximum operating temperature with no gripper deformation due to softening of the polymer material.

The current methods for studies of gripper displacement as the actuation voltage are simulation and imaging based approaches. The simulation based approach is very useful in the design process but cannot provide information about the real performance of the grippers (Tomasz & Sumelka, 2006). Although the imaging based method has been used to measure gripper displacement (Solano, et al., 2014; Nguyen, et al., 2004; Andersen et al., 2008), it has not been applied to all of the gripper devices reported previously (Pasumarthy et al., 2015; Chu et al., 2008b). In this paper, an image tracking based method is used to trace the position of each gripper tip separately and measure its displacement at a given actuation voltage.

The measurement of heater or gripper temperature was not carried out in some of the previous work (Solano, et al., 2014; Nguyen, et al., 2004; Andersen et al., 2008; Kim et al., 2004; Pasumarthy et al., 2015; Hamedi et al., 2013). On the other hand, it is important to determine the relationship between the applied voltage (power), the heater temperature and the displacement. This is because the glass transition temperature (Tg) of SU8 is 210°C and its degradation temperature is around 380°C (LaBianca

& Gelorme, 1995) which are much less than the melting temperature of the heater material (gold) which is 1064°C (Matula, 1980). Therefore, excessive heater temperature in gripper operation will cause degradation or damage to the gripper structure.

Three methods have been used to obtain the heater temperature, simulation, thermal imaging and measurement of resistance change respectively. The first method is useful but in some cases it is not accurate due to assumptions and inaccurate parameters of the materials and dimensions of the devices. This method has been used in the previous work (Chu et al., 2008a; Dodd et al., 2015; and Wang et al., 2015).

The second method was based on the temperature measurement using a thermal imaging camera. In this method, the camera was used to detect the thermal radiation from the heaters. This method has been used to estimate the temperature of the heater and the end-effectors (Dodd et al., 2015). The disadvantage is the limitation on the smallest detectable dimensions due to the diffraction effect (Astarita & Carlomagno, 2013). To process the data from the camera to determine the temperature of the object, accurate information from the material itself such as emissivity/reflection parameters is necessary. These parameters are different for different materials and in many cases are not easily available. If the object has multiple emissivities, the results do not represent the actual temperature (Goodman, 2016). In addition, thermal cameras are expensive and difficult to use in close loop control systems.

The change in the heater resistance as temperature can be used to measure the heater temperature. This method requires the value of TCR in order to determine the temperature based on the resistance change. This method has been used previously (Chu et al., 2008a; Chu et al., 2011; Colinjivadi et al., 2008; Solano & Wood, 2007; Zhang et al., 2012; Zhang et al., 2015) using the TCR of the bulk metal. However, in thin metal films the value of TCR is significantly less than that of the bulk material. It has been shown that the film thickness and resistivity have a negative correlation, but the thickness and TCR have a positive correlation (Yoshikatsu, 1970). In TCR measurements for gold thin films, Chronis and Lee reported a value of 3.36 PPM/°C (Chronis & Lee, 2005) which is very small as compared with the value of 0.0034/°C (Belser and Hicklin, 1959) for bulk gold material and was not consistent with the measured resistance change as temperature. On the other hand, it might be 0.00336/°C instead of 3.36 ppm/°C. This value is very close to the gold bulk value.

In this paper the results of characterization and testing of SU-8 based electrothermal actuated microgrippers with embedded microheaters are presented. The temperature coefficient of resistance (TCR) and the resistivity of the gold thin film microheaters were measured. It is shown that the TCR of the thin film material is much lower than that of the bulk material and therefore it is necessary to measure the TCR of the thin film heaters in order to determine the heater temperature for a given input voltage/current in operation of the microgrippers. The displacement between the gripper tips has been measured as a function of voltage using an image tracking method.

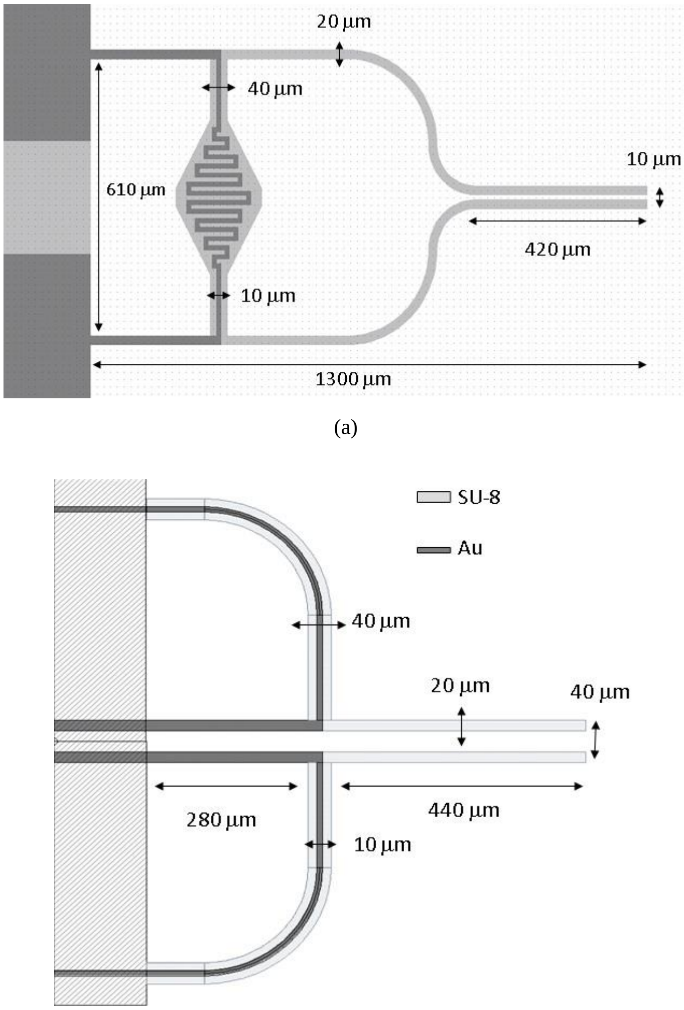
2. Design and fabrication

The microgrippers were designed using the principle of electrically driven thermal actuation in both operating modes: namely normally open operation and normally closed operation. In each design, the micro-heater is embedded in two SU-8 layers. The details of the design and fabrication work have been reported previously (Voicu & Műller, 2013a, Voicu & Műller, 2013b, Voicu et al., 2014).

The first microgripper (design 1) has a total length of 1300 μm as shown in Fig. 1 (a). The free arms were designed with a width of 20 μm. The microgripper operates by opening the arms to grip a micro-object when a voltage is applied cross the electrical contacts of the microheater. For the second one (design 2) shown in Fig. 1-b, the total length of the free arms is 760 μm. The width of the curved (hot) arms is 40 μm, while it is 20 μm for the straight (cold) arms. The initial opening in this case is 40 μm and the microgripper operates by closing the arms under electrothermal actuation. The line width of the gold microheaters is 10 μm and the width of the connecting sections between the heater elements and the bond pads is 14 μm in both designs.

The optimized design as described previously (Voicu & Műller, 2013a, Voicu & Műller, 2013b), consists of three layers, a metal layer (heater) is embedded in two SU8 based structure layers. In both cases the thicknesses of the Cr/Au/Cr films were 10 nm/300 nm/10 nm, and for the two SU-8 layers, both have a thickness of about 10 μm. The SU-8 based microgrippers were designed with embedded microheaters in the actuation structures of the grippers to improve thermal efficiency and to reduce the undesirable out of plane movement of the gripper tips.

For fabrication of the microgrippers a 3-mask based process and a lift-off method using the OmniCoat stripper (MicroChem/a, n.d.) in order to completely release the structures. First a thin layer of OmniCoat was deposited on a silicon wafer by spin-coating at 3000 rpm and then baked at 200°C on a hotplate for 1 minute. Then the SU-8 polymer was deposited on the wafer at 4000 rpm in order to obtain a thickness of about 10 μm. The wafer was soft-baked for 1 minute at 65°C and 2 minutes at 95°C. The SU8 layer was then exposed using the first mask. After the exposure, the wafer was post-baked at 65°C for 1 minute and 95°C for 3 minutes and then developed. 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 consisting of Cr/Au/Cr films of 10nm/300nm/10nm was evaporated and the heater and connection lines and pads were obtained using a lift-off process and an AZ photoresist.



(b)

Fig. 1 Design of the micromanipulators: (a) Design 1 for normally open mode operation (Voicu & Műller, 2013a); (b) Design 2 for normally closed mode operation (Voicu & Műller, 2013b)

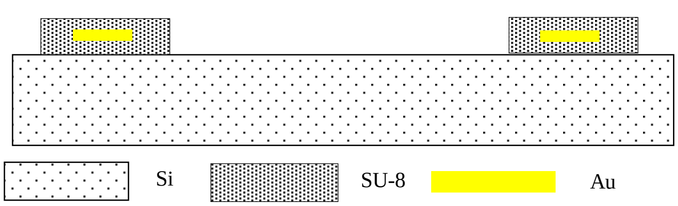


Fig. 2 Schematic cross section of the arms of the micrograppers after fabrication, not to scale

The second SU-8 layer was obtained using the same steps 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 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 using the piranha solution and deionized water for cleaning. Fig. 3 shows a schematic view of the cross-section of the gripper arms with the heater line, while Fig. 4 shows optical pictures of the fabricated microgrippers. It can be seen that the heater lines are well defined.

3. Testing and Characterisation

3.1. Resistivity and TCR in thin metal films

The ratio between the conductivity of the bulk material and in the thin film form is given in equation (1).

$$\frac{\sigma_o}{\sigma_{o'}} = 1 + \frac{3\,l}{8\,t}\,(1-p) \qquad t/l \gg 1 \qquad (1)$$

Where $\sigma_{o'}$ and σ_o are the conductivity of the thin film and the bulk material respectively. *l* is the length of the free path of electrons and *t* is the film thickness. *p* denotes the effect of elastic scattering of electrons at the surface (Sondheimer, 1952) which has a value between 0 and 1 (Horváth & Baankuti, 1988; Wissmann & Finzel, 2007). However, there are also other scattering effects such as scattering due to grain boundaries, uneven or rough surfaces, and impurities. These effects are represented by a constant, *C*, as shown in equation (2).

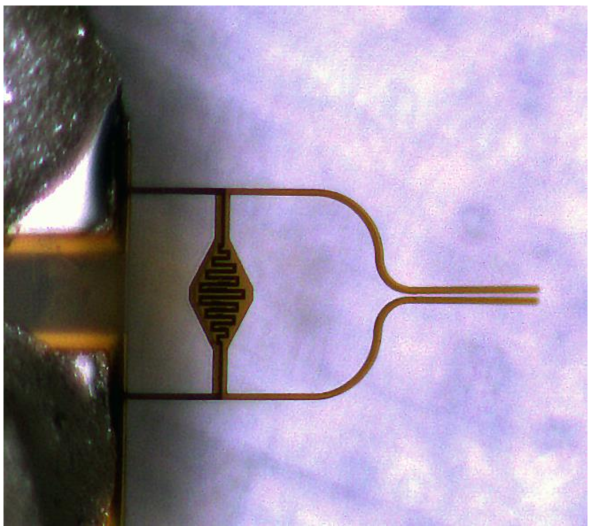
$$\rho_o{}' = C\,\rho_{o'} \qquad t \geq 2\,l_{bulk} \qquad (2)$$

Where $\rho_o{}'$ is the modified thin film resistivity, ρ_o is the calculated thin film resistivity, and C is a constant modifier. In addition, the temperature dependent resistivity is also affected as shown in equation (3).

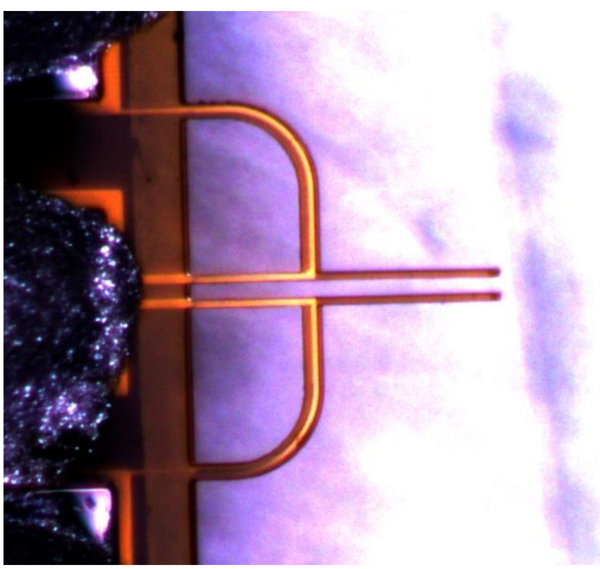
$$\rho'_t = \rho'_o \left[\frac{1}{\frac{\left[2\sqrt[\delta]{\frac{\gamma}{k\,T}} - b\right]\left(\frac{\tau_1}{\tau_2} - 1\right)}{2a+b} + 1} \right] \qquad (3)$$

Where ρ'_t is the resistivity at temperature *T* in Kelvin, *a* is the atomic radius, *b* is the spacing between stationary atoms, τ_1/τ_2 is the ratio of traveling time, δ is 1, *k* is Boltzmann's constant, and γ is the proportionality term in the energy equation (Lacy, 2011a; Lacy, 2011b). The value of C for an example for gold thin films has been calculated as 3.07 (Lacy, 2011a). As a result, it is necessary to measure the resistivity and the TCR experimentally since both are determined by the dimentions of the thin metal films and the specific scattering effects associated with the fabrication method and surrounding media.

The dimensions of the microheaters were measured using a microscope. Based on the results of the measurements we calculated the resistivity using equation (4). The results show that the resistivity of the thin film heaters is in the range of 6.2 μΩ·cm to 6.8 μΩ·cm. These values are close to the calculated value using both equation (2) and (3) which is 7.8 μΩ.cm. The value of l is 40 nm for gold, the thickness (t) is 300 nm, and the value of C can be determined to be 3.07 which is the same as that measured by Lacy (Lacy, 2011a). It is possible that the difference between the calculated and measured values of resistivity is due to the factors that the effects of the thin chromium layers and the film deposition method are not considered.



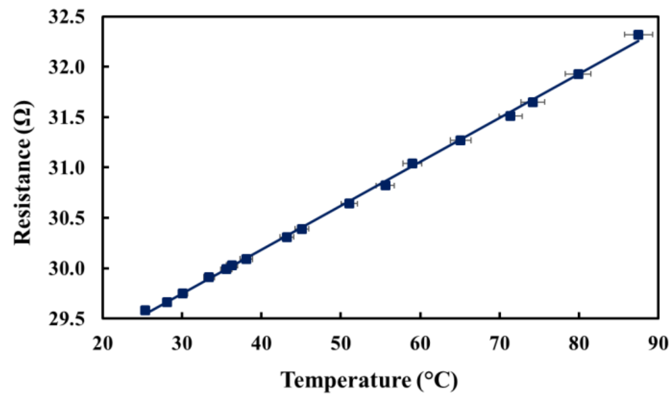
(a)



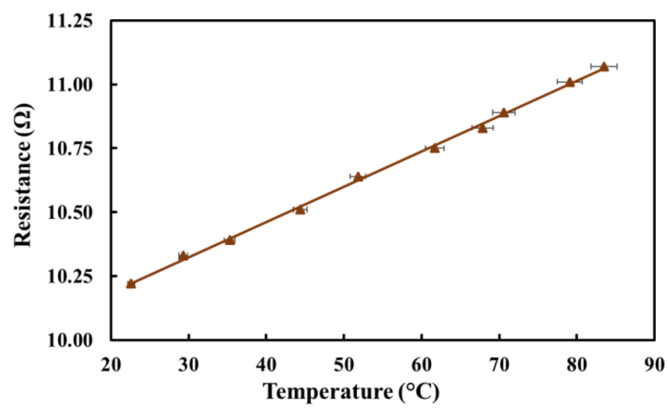
(b)

Fig. 3 Optical pictures of two electrothermal microgrippers with different modes of operation, (a) Design 1 for normally open mode operation and (b) Design 2 for normally closed operation

To obtain the relationship between the heater temperature and the applied voltage or electrical power, the temperature dependence of the heater resistance was determined. For measurements each microgripper was mounted on a microscope slide. Then electrical connections between the contact pads and thin wires were made using a silver loaded epoxy adhesive as shown in Fig. 3. The thin wires were subsequently connected to a small piece of PCB through which more secure wire connections were made for TCR and griper displacement measurements respectively.



(a) Design 1



(b) Design 2

Fig. 4 Results of heater resistance as a function of temperature

The TCR measurements were carried out by mounting the gripper for characterization in a small chamber which was placed on a hotplate. Two small thermocouples as temperature sensors were placed above and below the microgrippers and an average temperature was obtained. The resistance of the microheater was measured using a multimeter and the chamber temperature was recorded using the thermocouple. The heater resistance was measured over a range of values of temperature.

Fig. 4 shows the results of the measurements of the heater resistance as a function of temperature for both of the microgrippers. The room temperature resistance of the meander heater in Design 1 was about 29.5 Ω and it was about 10.3 Ω for the line shaped heater in Design 2. Based on the value of the line equation parameters and fit theme to the results for each design, the temperature coefficient of resistance (TCR) was determined. The values of TCR for Design 1 and Design 2 are 0.00147/°C and 0.00135/°C respectively. The TCR for Design 2 is slightly smaller than that of Design 1, the difference may be associated with the small width of the metal lines which may not be homogeneous after fabrication or due to the accuracy of placement of the temperature sensors for different gripper devices. There was variation in temperature distribution inside the heated chamber. However, both values are significantly smaller than the value of 0.0034/°C of the bulk gold material. The ratio of the TCR of the bulk material to that of the thin film has been found to be between 2.27 and 2.47. This is very close to the ratio of the thin film resistivity to the bulk resistivity which is between 2.5 to 2.74. This shows that the resistivity increases in the same ratio as the decrease of TCR.

The result agrees with what Belser and Hicklin have reported that the TCR of the gold thin film is about 1/3 to 2/3 of the bulk value (Belser and Hicklin, 1959). Thus it is necessary to measure the TCR of the microheaters when it is used to calculate the heater temperature for an applied voltage or electrical power. The use of the TCR value for bulk metal would lead to inaccurate calculation of the heater temperature. In this work the measured values of TCR were used to determine the relationship between the heater temperature and the gripper opening.

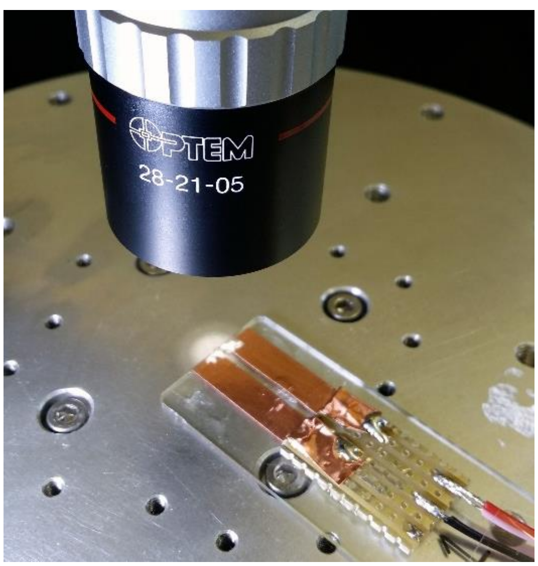


Fig. 5 An optical picture of a microgripper mounted on a robotic hexapod based plaform for displacement measurement using a microscope based vison system

3.2. Displacement measurements

For characterization of the microgrippers, each microgripper was mounted on a hexapod based robotic system as shown in Fig. 5. An optical microscope and high resolution camera in robotic system with an image tracking software were used to measure the displacement of the gripper tips to determine the change in the opening as the applied actuation voltage Fig. 6. The resolution of the camera based optical system with a 20x microscope objective was 0.3 µm.

The microgripper was connected to a DC power supply using a series resistance of 200 Ω to protect the gripper during the measurement process. Both the voltage and current of the microheater were measured and therefore the resistance could be calculated for each electrical input. Based the measured TCR and the resistance as described in section III A, the heater temperature was calculated for a given input voltage and hence the electrical power.

For each actuation voltage, the displacement of the gripper tips was measured using an image tracking software. Fig. 6 shows an illustration of the image tracking method. The tracking area is indicated by the green rectangle while the area of interest for measurement is indicated by the pink region. This method is capable of simultaneous measurement of two dimensional displacements, the change in the gripper tip displacement and the length of the arm can be determined at the same time. But in this work it was used to measure the gripper displacement since the change in the length of the arms was negligible. The results of the separation between the gripper tips are similar to that obtained on a Zygo interferometer.

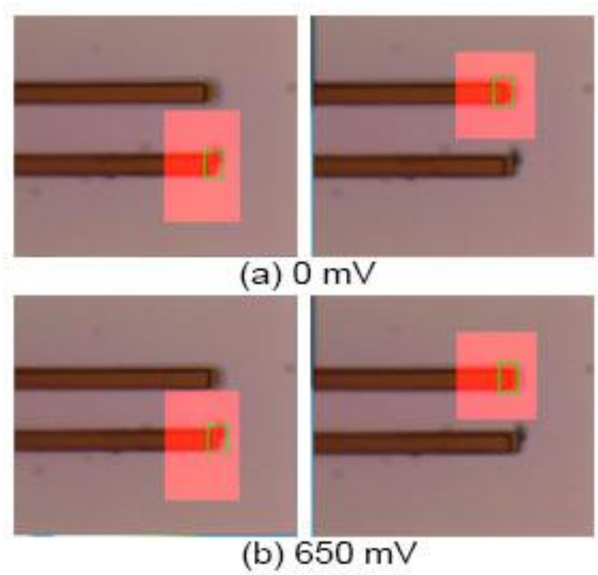
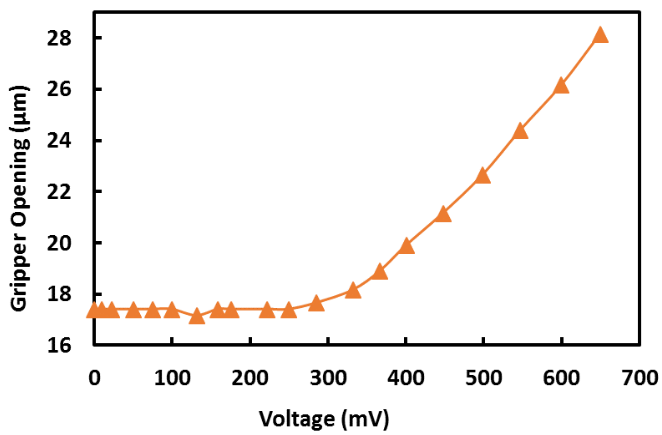


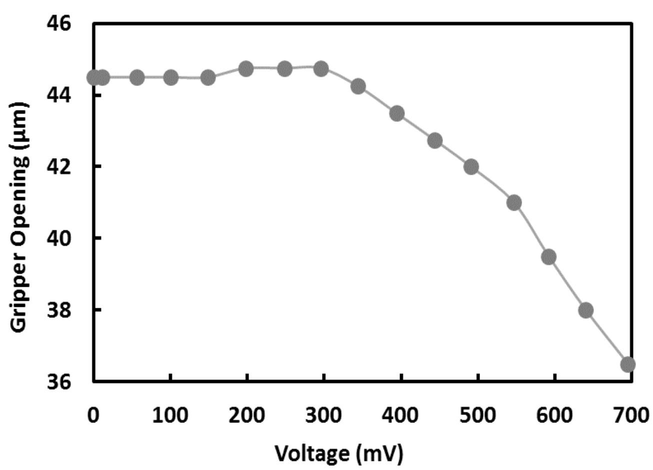
Fig. 6 Illustration of the image tracking method for displacement measurment using one of the microgrippers (Design 2). The tracking area is indicated by a green rectangle and the area of interest is shown by the pink region.

Fig. 7 shows the results of measurements of the opening between the gripper tips for both gripper designs. Over range of actuation voltage, the gripper opening of Deign 1 increases as the voltage from the initial value of about 17.5 µm to about 28.5 µm at the voltage of 0.65 V. For Design 2 the gripper opening decreases from the initial value of 44.5 µm to 36.5 µm at the actuation voltage of 0.69 V. The corresponding heater temperature was about 200°C in both cases. Therefore, the maximum displacement range is about 11 μm for Design 1 and 8 μm for Design 2 respectively. The thermal expansion of the gripper arms was also measured and the results for Design 2 are shown in Fig. 7(c). The increase was as much as 2.5 μm at the actuation voltage of 0.7 V.

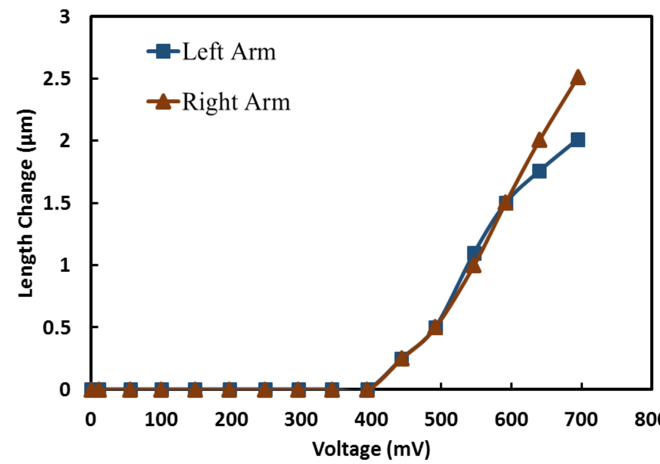
Fig. 8 shows the results of heater temperature as a function of the applied electrical power to the heater for both designs. As can be seen it is a linear behavior in both cases over the measured temperature range from room temperature to about 200°C. Further increase in electrical input was not investigated in each case since the heater temperature would exceed the glass transition temperature of SU8 material and material softening would occur.



(a) Design 1



(b) Design 2



(c) Design 2

Fig. 7 Measured results of gripper displacement and arm length change as a function of actuation voltage

The results in Fig. 8 show that the meander heater in Design 1 is more efficient than the line based heater in Design 2 since the required electrical power to reach the same heater temperature of 200°C was about 12 mW, much less than of electrical power of 35 mW for the latter. This is because the line heater in design 2 is more distributed and therefore causing faster heat dissipation.

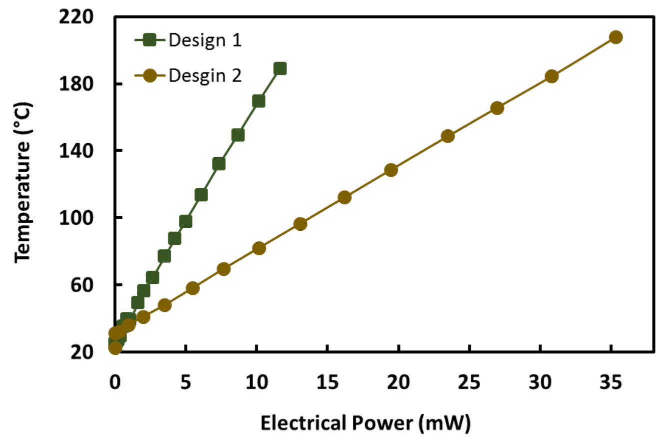


Fig. 8 Calculated results of heater temperature as a function of electrical power

3.3. Effect of temperature on SU-8 gripper structures

Design 2 was used to investigate the effect of temperature on the SU-8 based gripper structure in order to compare with the known behavior of the SU-8 material as temperature (LaBianca & Gelorme, 1995). The experiment was carried out using the same setup as for gripper displacement measurement. The voltage and current was measured using two multimeters and the pictures of the gripper was obtained using the vision system shown in Fig. 5. The applied voltage was raised in steps of about 50 mV and the heater temperature was determined in the same way as described in section 3.2. Fig. 9 shows pictures of the microgripper at room temperature, after heating to selected temperatures and after cooling to room temperature. At the heater temperature of 150°C, there is no noticeable change in both color or structure of the gripper as compared with that in Fig. 9(a). When the heater temperature was increased to 218°C which is in the range of the glass transition temperature of the SU-8 material, slight gripper deformation was observed as shown in Fig. 9(c). After the power of heater was removed, the gripper recovers to the original structure as shown in Fig. 9(d). A similar behaviour has been reported in literature (LaBianca & Gelorme, 1995).

Figs. 9 (e) and (f) show the pictures obtained at the heater temperature of 350°C and after the gripper was cooled to room temperature. The heater arm shows a dark region after the operation temperature reached to 350°C. The change in the color is non-recoverable. A slight shrinkage was also obtained because of loss of the SU-8 material by sublimation (MicroChem/b). This degradation effect is more clear in Fig. 10 which shows the effect of very high heater temperature (500°C) on the gripper structure, the gripper arms are completely out of shape bending downwards and it could no longer be operated.

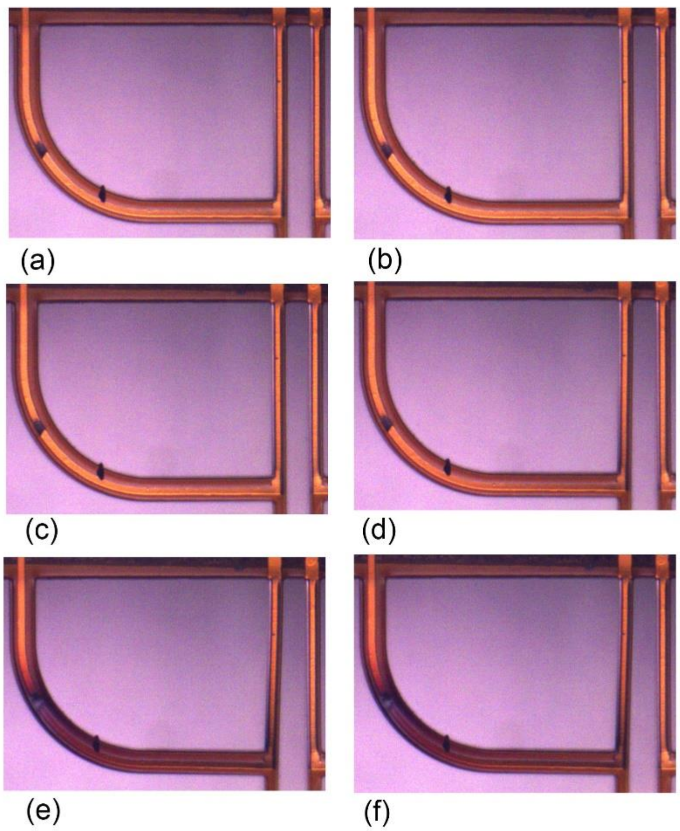


Fig. 9 Pictures of the microgripper (Design 2) at different heater temperatures. (a) room temperature, (b) 150°C, (c) 218°C, (d) power off after heater reaching 218°C, (e) 350°C and (f) power off after reaching 350°C.

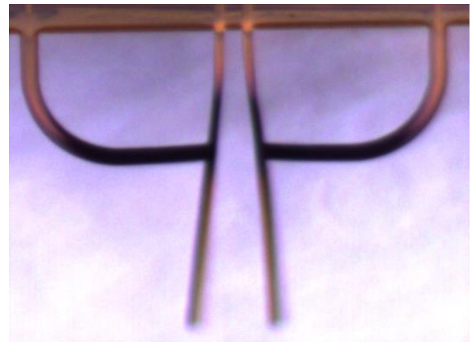


Fig. 10 Picture of microgripper after testing at heater temperature of 500°C

4. Conclusions

Measurement and characterization of electrothermal microgrippers have been carried out to investigate gripper displacement, the heater temperature and its effect on the gripper structure. The SU-8 based microgrippers were fabricated using a surface micromachining method with embedded microheaters for electrothermal actuation with improved thermal efficiency and stability. The TCR of the microheaters was measured independently and the value is smaller than that of the bulk gold material. The measured TCR was then used to determine the heater temperature in gripper operation at an applied voltage. An image tracking based method was used to measure the displacement of the gripper tips and hence the separation under an applied voltage. The resistivity of the gold thin film has been determined and it is higher than the bulk value as expected. It is very close to the value from theoretical calculations. The observed softening effect of the SU-8 material at 218°C indicates the correct measurement of temperature using the measured TCR of the thin film heaters. The results of testing at heater temperature of 350°C and 500°C show non-recoverable deformation and darkening of the SU-8 based gripper structure. The work provides useful information for future design and operation of electrothermal microgrippers with better performance and reliability. For example, a more distributed heater design would reduce the effect of high temperature at the location of the heater which is the case for Design 2 as shown in Fig. 9 (e) and (f) causing more degradation of the SU8 structure.

Acknowledgement

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