Design of a novel three arm electrothermal microgripper with multiple degrees of control

Muaiyd H. M. Al-Zandi* and Changhai Wang

Institute of Sensors Signals and Systems School of Engineering and Physical Sciences Heriot-Watt University Edinburgh UK

*Corresponding author

DOI: 10.5185/amlett.2018.2072
www.vbripress.com/aml

Abstract

A novel three arm microgripper design is presented in this paper. It is a SU-8 based design with integrated microheaters. It is composed of three microactuators: two are based on a design for bi-directional beam deflection and the other is a tri-directional actuator. The actuators are simulated and analyzed using COMSOL Multiphysics tool. The first actuator has displacement of about 12 µm and 35 µm respectively when heaters h1 and h2 are used in operation and the heater temperature is about 200°C. The second actuator has a displacement of about 12 µm in all three directions. This microgripper is flexible and can be used to grasp a wide range of sizes of micro-particles. In addition, it has more freedoms of control by using the different combinations of the 8 embedded microheaters for electrothermal actuation. Copyright © 2018 VBRI Press.

Keywords: Microgripper, micromanipulator, electrothermal actuator, SU-8.

Introduction

Well controlled microgrippers are versatile and essential tools to manipulate microscale objects because precise control in grasping or placement is not possible even by highly skilled manual operation. In addition, microgrippers eliminate the exposure to risk in biological laboratories [1–2]. Different materials have been used to fabricate microgrippers such as polysilicon [3], silicon [4], and polymer [5]. In addition, different actuation methods have been used to operate these microgrippers, such as external actuation [6] or integrated design based on pneumatic action [7], SMA (Shape Memory Alloy) [8], electrostatic force [9], piezoelectric effect [10] or joule heating effect [5]. However, the piezoelectric and electrostatic actuators require high voltage operation [11]. In addition, the externally actuated microgrippers require an assembly process for fabrication [6–8].

The joule effect device is based on translating the thermal expansion into actuation [12]. The appropriate material is SU-8, because it has a high CTE (Coefficient of Thermal Expansion) of 52 ppm/K) [13] comparing with silicon of 14.2 ppm/K [14] and polysilicon of 2.6 ppm/K [15], higher CTE results in higher actuation displacement.

The previous microgrippers have been designed based on either normally closed [16 - 17] or opened [18 - 20] mode operation in one dimension, or in two dimensions of movement [21] which have been employed to design four degrees of freedom devices [22]. However, these microgrippers were based on two moving arms which are used to grasp particles with limited capability and the maximum displacement of about 80 µm.

To design a flexible microgripper which can be used to grasp a wide range of micro-particles of different sizes, in this paper a novel three arm microgripper is presented.

Actuator Design

A bidirectional actuator design is shown in **Fig. 1(a)**. The movable arm is supported at two points, however each of them is connected to a microheater. By operating them separately, a different direction of beam deflection can be obtained as it is indicated by the arrows. The total length of this design is 1.3 mm, the arm width is 50 µm, and the thickness is 20 µm. The maximum displacement for both directions is directly proportional to the length of the moveable arm and the heater's length. This actuator has been designed for operation as an arms of a microgripper but it can also be used as a two-way micro-switch.

Fig. 1(b) presents a tri-directional actuator design. It consists of four heaters to achieve three directions of displacement by operating them in proper combinations. For example, when heater h3 or h4 is in operation, the arm deflects horizontally, and when the heaters h5 and h6 are used, the arm is deflected vertically. The effects of these heaters on actuation are indicated by the arrows. The total length of this actuator is 1.6 mm. The heater length and the arm length are directly proportional to the horizontal displacement, however the length of the arm does not affect the vertical displacement.

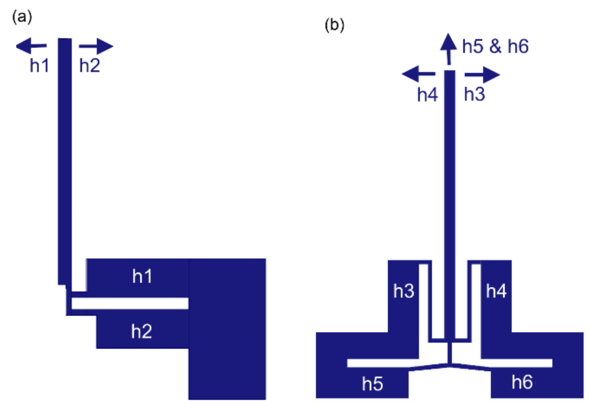

Fig. 1. Two actuator designs, (a) bi-directional actuator (b) tri-directional actuator. The arrows show the effect of each heater on the movement of the arms.

Modeling and simulation

The 3D module, Joule Heating and Thermal Expansion Multiphysics interface in COMSOL, is used to simulate the behavior of the actuator. The thickness of the two SU-8 layers was set to be 10 µm each, and the metal layer of (Cr/Au/Cr) to be 10/300/10 nm. The properties of the SU-8 and metal are shown in **Table 1**. The TCR and the resistivity values for the metal are those of pervious measurement [18 - 19]. Since the chromium films are much less than the gold layer, so the other properties of the metal layer (heaters) assumed to be those of the gold. The change in the conductivity with temperature in the metal layer is given in Eq. 1, where σ *(T)* is the conductivity of the metal layer as a function of temperature, α is the measured TCR, T is the temperature, T_{ref} is the reference temperature of the measured TCR and it is 20°C. For the air medium, the pre-set values in COMSOL are used.

To consider the air cooling effect on the actuators, the structures are surrounded with a cubic box of air with dimensions of 1 cm. The cubic surfaces are set to have a convective heat flux and the heat transfer coefficient is set to be 10 W/(m^2.K).

Table 1. Properties of SU-8 and metal layers.

SU-8 properties [17, 23-26]		
Parameter	**Value**	**Unit**
Young's modulus	2	GPa
Poisson's ratio	0.22	
Thermal conductivity	0.3	W/(m·K)
Coefficient of thermal expansion	52x10^{-6}	1/K
Density	1.2	g/cm^3
Heat capacity at constant pressure	1.2x10^3	J/(kg·K)
Metal layer (Cr/Au/Cr) properties [18,19,27]		
Parameter	**Value**	**Unit**
Gold Thermal conductivity	318	W/(m·K)
Density	19.3	g/cm^3
Heat capacity at constant pressure	129	J/(kg.K)
TCR	0.00147	1/°C
Resistivity	6.8	µΩ.cm

$$\sigma(T) = \frac{1}{\rho_\circ(1 + \alpha(T - T_{ref})} \quad (1)$$

The solid mechanics study was only applied to the SU-8 structures because the air and the metal layer have negligible effect on the produced beam deflection, while the electric current simulation is limited to the metal heaters. In addition, meshing is set to the COMSOL's physics-controlled configuration with normal element sizes.

Results and discussion

Fig. 2 shows the results when each heater is operated separately for the actuator design shown in **Fig. 1(a)**. At the actuation voltage of 1.2 V on heater h1 the average temperature is about 200°C and the beam deflection is about 35 µm. While at the same voltage for heater h2, the same average temperature is produced but the beam was deflected in the opposite direction for about 11 µm. Therefore for a gripper using a pair of the actuator design shown in **Fig. 1(a)**, a maximum displacement of 70 µm can be obtained in closing mode and about 22 µm in opening mode.

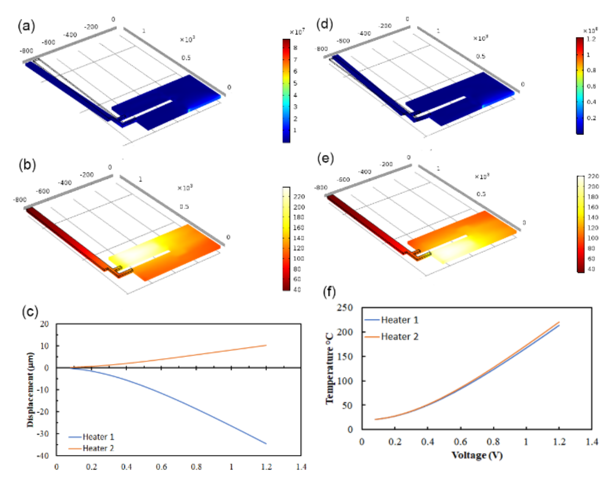

Fig. 2. Simulation results of the bi-directional actuator (Fig. 1(a)). (a) displacement and (b) temperature distribution when a voltage of 1.2 V is applied to heater, (c) displacement under the operation of each heater separately, (d) and (e) displacement and temperature distribution when heater h2 is driven at 1.2 V, and (f) average temperature in heaters (h1 and h2) when they are operated separately.

Fig. 3 shows the simulation results for the tri-directional actuator design shown in **Fig. 1(b)**. When the temperature of heater h3 is increased to about 200 °C, the deflection of beam tip is 12 µm to the right side when a 1.2 V is applied. In a symmetric fashion when the same voltage produces the same average temperature in heater h4, but with 12 µm of displacement to the opposite (left) side. Heaters (h5 and h6) are designed to work simultaneously. Applying 1 V of voltage to each of them, the average temperature in these heaters is about 200 °C, a deflection of about 12 µm of the beam is obtained in the vertical direction.

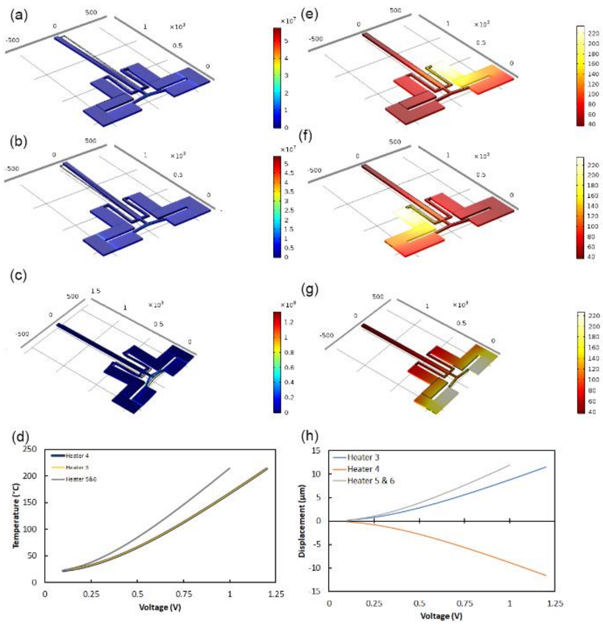

Fig. 3. Simulation results of the tri-directional actuator (Fig. 1(b)). (a) and (e) deformation and temperature distribution when heater h4 is operated, (b) and (f) deformation and temperature distribution when heater h3 is operated, (c) and (g) deformation and temperature distribution when heaters h5 and h6 are used, (d) avarege temperature in each heater when they are in operation, and (h) displacement of the beam tip when each heater is operated.

By combining two actuators of the design shown in **Fig. 1(a)** and one actuator of the design shown in **Fig. 1(b),** a novel 3 arm microgripper with multiple degrees of control is designed as shown in **Fig. 4**. The operating characteristics and control of the gripping tips can be determined by the analysis of the operating modes of the individual arms as shown in **Figs. 2** and **3**.

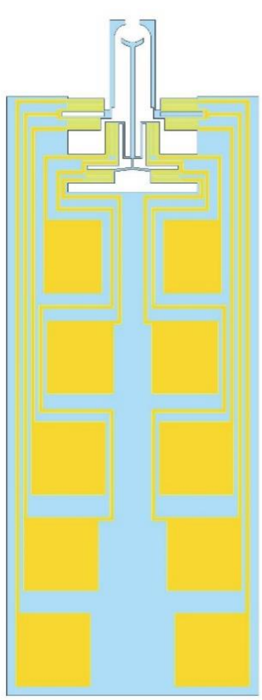

Fig. 4. Schematic layout of the three arm microgripper showing the heaters and conductor lines (yellow) and the SU8 based structure (blue).

In this paper we have presented the results of design and simulation of two actuator designs which can be combined to develop a novel 3 arm microgripper with multiple degrees of control. The microgripper can be fabricated for cell and particle manipulation and assembly applications. Horizontally the end tips of the two outer arms can each be deflected by up to 35 μm or 12 μm depending on the actuation voltage. The tip of the middle beam can be operated in three directions with the maxiumum deflection of 12 μm.

References

1. Zhang, Y.; Xu, Q. *IEEE Transactions on Control Systems Technology*, vol. 25, no. 2, pp. 728-735, March 2017.
   DOI: 10.1109/TCST.2016.2569567
2. Kalaiarasi, A. R.; Thilagar, S. H.; *Proceedings of 2012 IEEE/ASME 8th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications*, Suzhou, 2012, pp. 7-11.
   DOI: 10.1109/MESA.2012.6275528
3. Kim, C.; Pisano, A.; Muller, R.; Lim, M. *IEEE 4th Technical Digest on Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, USA, 1990, pp. 48-51.
   DOI: 10.1109/SOLSEN.1990.109818
4. Chen, T.; Chen, L.; Sun, L. *2009 IEEE International Conference on Robotics and Automation*, Kobe, 2009, pp. 2989-2994.
   DOI: 10.1109/ROBOT.2009.5152195
5. Chronis, N., & Lee, L. *17th IEEE International Conference on Micro Electro Mechanical Systems. Maastricht MEMS 2004 Technical Digest*, 2004, pp. 17-20.
   DOI: 10.1109/MEMS.2004.1290511
6. Mousavi, M. M. S.; Pasquale, G. De; Somà, A.; Brusa, E. *2011 Symposium on Design, Test, Integration & Packaging of MEMS/MOEMS (DTIP)*, Aix-en-Provence, 2011, pp. 356-361.
   URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6107970&isnumber=6107967
7. Bütefisch, S.; Seidemann, V.; Büttgenbach, S.; *Sensors & Actuators: A. Physical*, 97, pp.638–645.
   DOI: 10.1016/S0924-4247(01)00843-3
8. Kohl, M.; Krevent, B.; Just, E. Sensors and Actuators A: Physical, vol. 97 – 98, April 2002, pp. 646-652.
   DOI: 10.1016/S0924-4247(01)00803-2
9. Kim, Chang-Jin; Pisano, A. P.; Muller, R. S. *Solid-State Sensors and Actuators, 1991. Digest of Technical Papers, TRANSDUCERS '91., 1991 International Conference on*, San Francisco, CA, USA, 1991, pp. 610-613.
   DOI: 10.1109/SENSOR.1991.148952
10. Grossard, M.; Rotinat-Libersa, C.; Chaillet N.; Boukallel, M. *IEEE/ASME Transactions on Mechatronics*, vol. 14, no. 1, pp. 32-45, Feb. 2009.
    DOI: 10.1109/TMECH.2008.2003437
11. Chronis, N. & Lee, L.P. *Journal of Microelectromechanical Systems*, vol. 14, no. 4, pp. 857-863, Aug. 2005.
    DOI: 10.1109/JMEMS.2005.845445
12. Guckel, H.; Klein, J.; Christenson, T.; Skrobis, K.; Laudon, M.; Lovell, E. G. *Technical Digest IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, USA, 1992, pp. 73-75.
    DOI: 10.1109/SOLSEN.1992.228273
13. Zhang, X.; Wu, Y.; Miao, X.; Zhang, C.; Ding, G. *2010 IEEE 5th International Conference on Nano/Micro Engineered and Molecular Systems*, Xiamen, 2010, pp. 362-365.
    DOI: 10.1109/NEMS.2010.5592235
14. Andersen, K. N.; Petersen, D. H.; Carlson, K.; Molhave, K.; Sardan, O.; Horsewell, A.; Eichhorn, V.; Fatikow, S.; Boggild, P. IEEE Transactions on Nanotechnology, Jan. 2009, Vol.8(1), pp.76-85
    DOI: 10.1109/TNANO.2008.2006558
15. Pasumarthy, A.; Dwivedi, A. K.; Islam, A. *2015 International Conference on Electrical, Electronics, Signals, Communication and Optimization (EESCO)*, Visakhapatnam, 2015, pp. 1-5.
    DOI: 10.1109/EESCO.2015.7253751

16. Nguyen, N.; Ho, S.; Low, C. *Journal of Micromechanics and Microengineering*, 2004 14(7), pp.969-974.
DOI: 10.1088/0960-1317/14/7/018
17. Somà, A.; Iamoni, S.; Voicu, R.; Müller R.; Al-Zandi, M. H.; Wang, C. *Microsystem Technologies*.
DOI: 10.1007/s00542-017-3460-3
18. Al-Zandi, M. H.; Wang, C.; Voicu, R.; Muller, R. *Microsystem Technologies*
DOI: 10.1007/s00542-017-3298-8
19. Al Zandi, M. H.; Wang, C.; Voicu, R. C.; Muller, R. *Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP)*, Budapest, 2016
DOI: 10.1109/DTIP.2016.7514880
20. Solano, B.; Merrell, J.; Gallant, A.; Wood, D. *Microelectronic Engineering*, 124, pp.90-93.
DOI: 10.1016/j.mee.2014.06.002
21. Shen, X.; Hu, Y.; Zhou, L.; Wang, Z.; Chen, X. *Integrated Ferroelectrics, 153(1), pp.9-22.*
DOI: 10.1080/10584587.2014.902281
22. Greminger, M.; Sezen, A.; Nelson, B. *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*, 2814-2819.
DOI: 10.1109/IROS.2005.1545137
23. Voicu, R.; Al Zandi, M.; Müller, R.; Wang, C. l 2017 J. Phys 2017.: Conf. Ser. 922 012006
DOI: 10.1088/1742-6596/922/1/012006
24. MicroChem 2016 SU-8 2000 Permanent Epoxy Negative Photoresist [Online]
http://www.microchem.com/
25. Lai, Jian-Lun; Liao, Chien-Jen; John Su, Guo-Dung *Sensors*, vol. 12, no. 12, 2012, pp. 16390–16403.
DOI: 10.3390/s121216390
26. Roch, I *Journal of Micromechanics and Microengineering*, vol. 13, no. 2, 2003, pp. 330–336.
DOI: 10.1088/0960-1317/13/2/323
27. Touloukian. Y. S. Thermophysical Properties of Matter. Vol. 1, 1970.

