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Fabrication of an electro-thermal micro-gripper with elliptical cross-sections using silver-nickel composite ink

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ABSTRACT

This paper proposes a rapid fabrication process for miniaturized electro-thermal grippers by using silver-nickel composite ink. Thick resistive structures are dispensed on a silicon wafer by a dispenser, and the parameters of the dispenser can be controlled for different thicknesses of hot and cold arms in a micro-gripper. The fabricated single layer structures are almost symmetric about a central plane of symmetry, thus largely suppressing the out-of-plane deflection. Due to cross-sectional area difference of the cold and hot arms, the micro-gripper can be driven by applying dc voltages. Electrical and mechanical behaviors of the micro-grippers are simulated and tested, and the simulation results are in accordance with the experiment results. The simulated maximum temperature is 155 °C, and occurs at the hot arms with an input voltage of 1.54 V. The measured displacement of the micro-gripper is observed to be 311 μm for an applied current of 0.26 A with maximum power dissipation of 0.4 W. The fabricated micro-gripper can grip a small styrofoam ball with a diameter of 1.3 mm between both tips.

1. Introduction

With the advance of miniaturization technology, development of micro-grippers with precise manipulation attracts wide attention for applications in micro-surgery, micro-robotics, microfluidics, and micro-assembling. A micro-gripper is designed to grip and transport a micro object without any damage. Among various driving mechanisms, electrostatic, piezoelectric, shape memory, and electro-thermal effects are most commonly used in micro-grippers [1]. For electrostatically driven micro-grippers [2,3], high voltage is required for the actuation, and pull in effect usually limits the displacement. For piezoelectrically driven micro-grippers [4,5], displacement amplification mechanisms are usually required to amplify the small output of piezoelectric actuators, and it occupies large volume with the use of multilayer PZT stacks. For micro-grippers using shape memory alloy [6], it suffers from poor fatigue and hysteresis properties.

Compared with the above mechanisms, electro-thermally driven micro-gripper provides large opening displacements at low voltages, thus making it appropriate for bio-applications [7]. Therefore, more and more researchers are working on various fabricating techniques for electro-thermal micro grippers. Riethmuller and Benecke, [8] used bimetallic materials with different coefficients of thermal expansion to drive a 500 μm long micro cantilever structure. When supplying Joule heat, the deflection is around 74 μm for an input power of 130 mW. Then, Parameswaran et al. [9] used a CMOS process to fabricate a dual layers cantilever structure, composed by polysilicon and silicon. An elastic deflection of 4 μm with 5.6 mW input power was achieved for frequencies up to 1.5 kHz. Chronis and Lee [10] developed a micro-gripper using thin metallic structure and high thermal expansion coefficient material, and it can be operated with small average temperature elevations at 1–2 V. Lu et al. [11] reported nanotube micro-opto-mechanical grippers by using a photomechanical actuation mechanism introduced to SU8 polymer structures. The tip opening is 24 μm under 0.8 W of laser stimulus from a 430-μm-long gripper. Duc et al. [12] developed a silicon-polymer electro-thermal actuator which consists of a silicon comb structure with an aluminum heater on top and SU-8 polymer between the comb fingers. The jaw displacement is 32 μm at an input voltage of 4.5 V with a maximum average temperature of 176 °C. However, for using a hybrid or multilayer structures with different expansion coefficients, initial warping [13] or out-of-plane deflection usually occurs.

Several researches studied the electro-thermal actuation based on the asymmetrical thermal expansion of the micro-structures. Guckel et al. [14] used deep X-ray lithography and metal plating to fabricate a thermally activated beam flexure with a very high aspect ratio. By resistive heating, the structure with differ-

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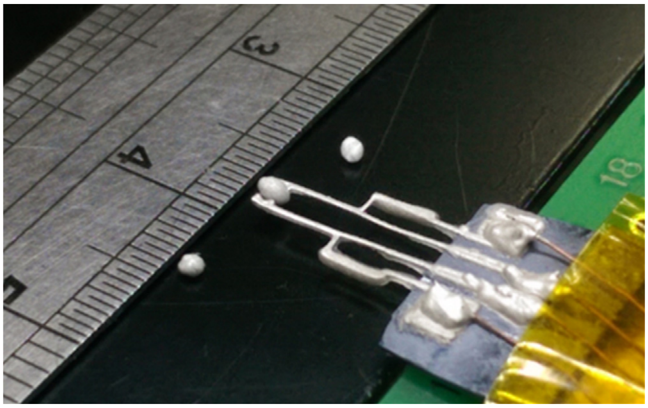

Fig. 1. Photo of the fabricated gripper, gripping a ball with a diameter of 1.3 mm between both tips.

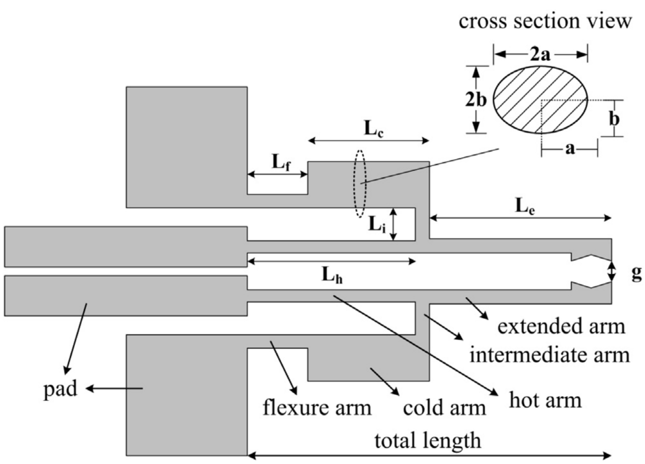

Fig. 2. Schematic drawing of the micro-gripper.

ent cross-sections deflects due to asymmetrical thermal expansion. Pan and Hsu [15] developed a micro-actuator made of polysilicon with two different arm lengths. It can produce 20 μm displacement with 0.6 mJ heat dissipation under 10 V_{dc} driving voltage, and the temperature is lower than 600 °C.

Typical manufacturing techniques for micro-grippers are using semiconductor processes, but the processes to make thick structures are usually complicated. In this paper, we proposed a rapid prototyping fabrication method for thick electro-thermal structure by using simple dispensing technology. The parameters of the dispenser can be controlled in real-time, so different thickness for cold and hot arms can be fabricated in a single process, which largely reduces the fabrication complexity. In addition, the electrical and mechanical behaviors of the micro gripper were characterized, and the simulation results are in accordance with the experiment results. The fabricated micro gripper can successfully grip a small styrofoam ball with a diameter of 1.3 mm, as shown in Fig. 1.

2. Theory

The thermally driven micro-gripper is designed according to a typical hot-and-cold-arm actuator design [10,14], but with elliptical cross sections (Fig. 2). When applying voltage to different metal structures, different thermal expansions are induced due to resistive heating, causing the structures to deflect. The resistance of the metal structure with uniform cross section is proportional to the length and inversely proportional to the cross-sectional area, so the total resistance of the micro-gripper can be expressed by the following equation:

$$R = \rho\left(\frac{L_h}{A_h} + \frac{L_i}{A_i} + \frac{L_c}{A_c} + \frac{L_f}{A_f}\right), \tag{1}$$

where R is the total resistance for a set of arms; ρ is the resistivity of the material; L_h, L_i, L_c, and L_f, are the lengths of the hot, intermediate, cold and flexure arms, respectively; A_h, A_i, A_c, and A_f, are the cross-sectional areas of the hot, intermediate, cold and flexure arms, respectively.

If electric current I flows through a resistive medium, electrical energy will be converted into heat energy due to Joule heating. We will consider this energy transfer as a heat generation inside the structure. The differential form of the Joule heating equation, calculated at a particular location, can be written by $\dot{g} = d\dot{G}/dV = \rho I^2/A^2$, where $\dot{g}$ is the heat generation per unit volume of a medium, and $\dot{G}$ is the total heat generation inside the medium. The one-dimensional heat equation for the medium can be given by Ref. [16]

$$-\frac{1}{A}\frac{d\dot{Q}}{dx} + \dot{g} = \rho_m c\frac{dT}{dt}, \tag{2}$$

where ρ_m is the volumetric mass density, and c is the specific heat of the medium. In addition, the rate of heat conduction through a medium can be expressed by Fourier's law of heat conduction, $\dot{Q} = -kAdT/dx$, where heat is conducted in the direction of decreasing temperature. Therefore, the steady-state one-dimensional heat equation and general solution, with constant thermal conductivity k, can be simplified as [16–18]

$$\frac{d^2T}{dx^2} + \frac{\dot{g}}{k} = 0 \tag{3}$$

$$T(x) = -\frac{\dot{g}}{2k}x^2 + C_1x + C_2 \tag{4}$$

where C_1 and C_2 can be determined by the boundary conditions.

For thermal analysis, since the highest temperature occurs at the hot arm, the thermal behavior of the hot arm is characterized. The temperatures of the mechanical anchor points are defined as T_a. By using $C_1 = (1/2k) * (\rho I^2/A_h) * (L_h/A_h + L_i/A_i + L_c/A_c + L_f/A_f)$ and $C_2 = T_a$ [18], the maximum temperature T_m and the corresponding location X_m in the hot arm can be derived by setting the derivation of Eq. (4) to zero, and can be written by

$$T_m = T_a + \frac{\rho I^2}{8k}\left(\frac{L_h}{A_h} + \frac{L_i}{A_i} + \frac{L_c}{A_c} + \frac{L_f}{A_f}\right)^2 \tag{5}$$

$$x_m = \frac{A_h}{2}\left(\frac{L_h}{A_h} + \frac{L_i}{A_i} + \frac{L_c}{A_c} + \frac{L_f}{A_f}\right) \tag{6}$$

3. Fabrication

For fabricating the electro-thermal micro-gripper, a 3-axis dispenser was utilized to fabricate cold arms, hot arms, and gripper tips by using resistive ink and supporting materials. The advantages of this fabrication process are thick device and simple fabrication. For different feature size requirements, the parameters of the dispenser including needle size, pressure, temperature, and speed can be controlled in real-time. The deposition parameters resulted in

Table 1
Deposition parameters of the micro-gripper.

Parameter	Speed (mm/s)	Pressure (kg/cm^2)
Hot arm	7	1.2
Cold arm	0.48	1.2