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A Novel Three-State Electrothermally Actuated Microgripper

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Abstract—This work demonstrates a novel multi-configurable three-state electrothermally-actuated microgripper. The state of the gripper refers to the electrical configuration of the hot and cold arms as well as the mechanical mode of operation. The gripper has three basic electrical configurations and subsequent operational modes; the opening, the partial closing state, and the full closing state. The first mode of operation achieves a maximum opening per-arm displacement of 1.06 µm when a maximum DC voltage of 7 V is applied. In the second operational mode (the partial closing state), the gripper achieves a maximum closing per-arm displacement of 1.26 µm for a maximum applied DC voltage of 9 V. This mode is also thought to exhibit significant out-of-plane jaw displacement. The third mode of operation achieves full tip-tip contact for an applied DC voltage of 9 V which corresponds to a per-arm closing displacement of 2.53 µm. In the unpowered configuration, the jaw tip-tip distance is 5.05 µm. The gripper is fabricated using a standard PolyMUMPs process and is manufactured out of polycrystalline silicon.

Keywords-microgripper, three-state microgripper, MEMS, PolyMEMPs.

I. INTRODUCTION

The continued research in microelectromechanical systems (MEMS) has paved the way for previously unimaginable applications through the use of microdevices. MEMS devices offer many benefits such as increased precision for micro-length scale object manipulation, fast response time, and ease of implementation with other MEMS devices [1]. These benefits have led researchers to make great strides in many engineering applications such as micro-energy harvesters, micropumps, particle sorters, microgrippers, microsensors, and various types of microactuators [2]–[8].

In this paper we present a novel microgripper. Microgrippers allow for fine particle control in a compact design with low power consumption, using compliant structures and various micro-actuator designs. This means that microgrippers are useful for applications involving object manipulation, material characterization, and microsurgery [6], [9]. Occasionally, amplification structures are used to increase the motion range of microgrippers.

Microgrippers generally rely on one of four types of micro-actuators: namely electrostatic, electromagnetic, piezoelectric, and electrothermal actuators [10]. Each actuator type has benefits and limitations. Electrostatic actuators are based on applying a capacitive electric field to produce actuator displacement. Electrostatic actuators have a high-frequency response and generally consume little power as demonstrated in[11]–[13]. Electromagnetic actuators use the Lorentz force to produce a magnetic field which is used for displacement. They offer quick actuator response and can create large displacements[14], [15]. Piezoelectric actuators rely on piezoelectric materials responding to an applied voltage, which causes local strain change in the piezo material, causing displacement. They have high sensitivity and do not require a large driving voltage. Piezoelectric actuators are known to produce small displacements and often require amplification techniques to increase displacement range [16]–[18].

Electrothermal actuators rely on temperature gradients in the material that causes thermal expansion which in turn causes displacement as shown in [19]–[22]. Electrothermally actuated microgrippers generally have large driving forces and large displacements under low driving voltages as demonstrated in [23], [24]. An electrothermally actuated microgripper with an integrated force sensor is proposed in [25], [26]. A "dual-action" electrothermal microgripper which allows for both the opening and closing of the gripper jaw was proposed and demonstrated in [27]. Two electrothermal microgripper designs that eliminate the parasitic resistance of the cold arm and produce large jaw displacements at low hot-arm temperatures were demonstrated in [28]. While electrothermally actuated MEMS devices generally have a large displacement to voltage ratio, they still benefit from displacement amplification techniques as demonstrated in [29]–[32].

The out-of-plane motion of the jaw is a phenomenon that can be both beneficial and detrimental to gripper operation and must be accounted for when designing microgrippers. Out-of-plane motion can affect the in-plane gripping range and effectiveness and is, therefore, undesired for many applications. It can also make it more difficult to grip objects that are at the same height as the gripper jaw. A polymer thermal microgripper that exhibits reduced out-of-plane displacement can be seen in[33]. Out-of-plane jaw motion can also be beneficial as it allows for more degrees of freedom when controlling the jaw, allowing for height correction should an object be positioned above the initial jaw height.

Most existing microgripper designs only have one or two states of actuation and movement. Furthermore, many existing designs lack any sort of capability to finely control the out-of-plane motion of the jaw. This paper presents a novel three-state electrothermal microgripper which can perform controlled in-plane, out-of-plane, and combined jaw motion. The three states include an opening state, a partial closing state, and a full closing state. The microgripper has a low operational voltage range of 9 V_{DC} and uses five arms of various lengths and thicknesses to achieve the three-state operability. The proposed design was fabricated and experimentally tested by sweeping the applied voltage and measuring the jaw displacement to verify the performance of the microgripper.

II. Methodology

A. Design

The microgripper is manufactured out of two primary polysilicon layers, designated Poly1, and Poly2, as per the PolyMUMPs design rules, Fig.1a. The thickness for poly1 and poly2 silicon layers are 2µm and 1.5µm, respectively. The top-view of the fabricated microgripper taken by a microscope can be seen in Fig. 1b.

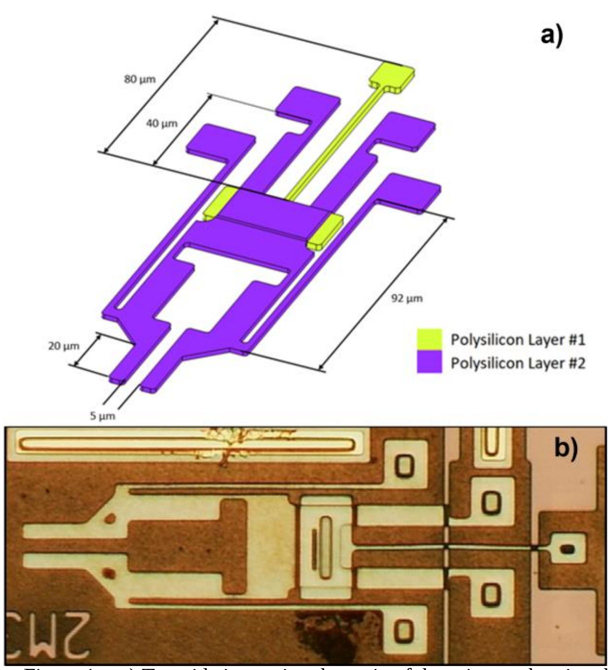

Figure 1. a) Top-side isotropic schematic of the gripper, showing the polysilicon 1 (Poly1) and polysilicon 2 (Poly2) layers. b) Top-microscopic image of the prototyped microgripper that was used for the experimental testing.

The microgripper has five arms that can be powered to induce in-plane and out-of-plane motions, which can both open and close the jaw. The hot arms width and length are 1.5µm and 67.5µm for poly1 and 2µm and 92µm for poly2. The width of the cold arms is 2.5µm at the narrow part and 7µm at the wide part. The arms are electrothermally actuated by employing joule-heating with power being applied on the electrodes at the anchors. The electrical configurations for each of the mechanical operational modes can be seen in Fig. 2.

The first electrical configuration corresponds to an operational mode that forces the gripper jaw to open as the voltage is increased. The second configuration forces the gripper jaw to partially close in-plane and exhibits out-of-plane motion. The third configuration forces the gripper jaw to fully close.

B. Experimental Setup

The performance of the gripper was tested by securing the chip on a probe positioning apparatus and applying electrical signals to various electrical contact pads on the substrate which are connected to specific anchors (as seen in Fig. 2). The test setup is shown in Fig. 3. The electrical power was applied with an Agilent E3631A DC power supply.

The gripper was then viewed under a microscope which is connected to a computer. Images were taken at increasing DC voltage values and analyzed using ImageJ photo analysis software. The DC voltage was varied from 0–7V for the opening state and 0 – 9 V for the partial and full closing states.

III. Experimental Results and Discussion

The tip-tip jaw displacement was measured as the voltage was swept for each of the three configurations and the results are shown in Fig. 4. Applying a voltage causes the jaws to open in the first mode while causing the jaws to close in the second and third modes.

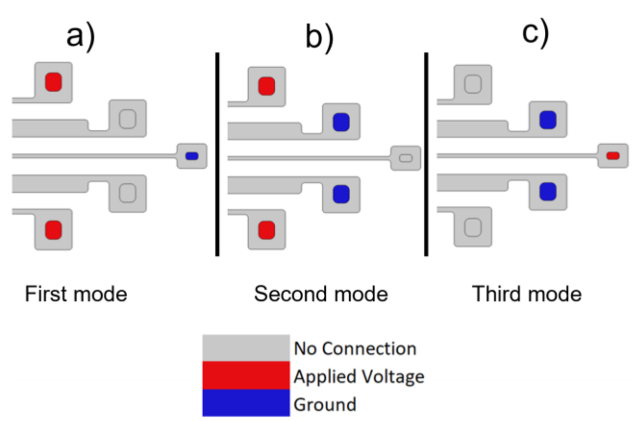

Figure 2. Image showing the electrical configurations which correspond to the three mechanical modes of operation of the microgripper. a) The first configuration refers to the opening state; b) the second configuration refers to the partially closing state, and c) the third configuration refers to the full closing state.

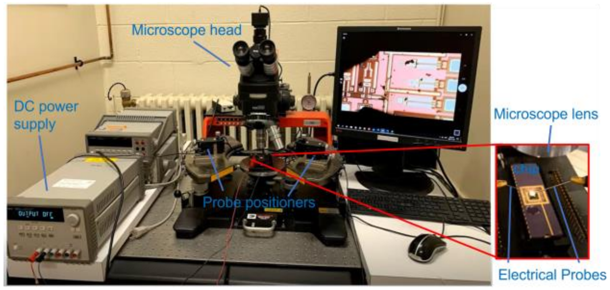

Figure 3. Test setup.

In the first mode, the opening state, the gripper experiences an opening per-arm displacement of 1.06 µm for a maximum DC voltage of 7 V. In the second mode, the partially closing state, the gripper achieves a maximum closing per-arm displacement of 1.26 µm for a maximum DC voltage of 9 V. The third mode, the fully closing state, gives the largest jaw displacement when voltage is applied and allows for the tips to make full contact, corresponding to a per-arm displacement of 2.53 µm for a maximum applied voltage of 9 V. Fig. 4 a and b show jumps in the jaw displacement for the opening and partial closing states. It is thought that the gripper experiences out-of-plane motion at 3, 4, 6, and 8 V.

Future experimental work should focus on characterizing the gripper such as measuring the out-of-plane displacement in all the three powered modes.

IV. Conclusion

A novel three-state electrothermally actuated microgripper was designed, fabricated, and tested. The state of the gripper refers to the electrical configuration of the hot and cold arms as well as the mechanical mode of operation. In the first state, the jaw opens. In the second state, the jaw partially closes and in the third state, the jaw fully closes. The first mode of operation achieves a maximum opening per-arm displacement of 1.06 µm when a DC voltage of 7 V is applied. In the second operational mode, the gripper achieves a maximum closing per-arm displacement of 1.26 µm for a DC voltage of 9 V. The third mode of operation achieves full tip-tip contact which corresponds to a per-arm closing displacement of 2.53 µm for a DC voltage of 9 V. The gripper is thought to have out-of-plane motion.

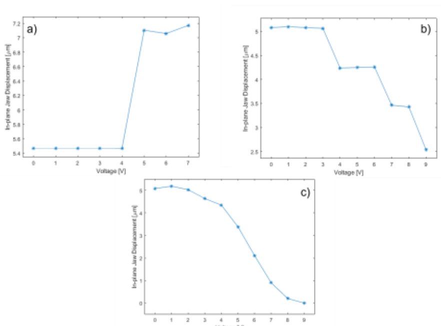

Figure 4. Graphs showing the tip-tip in-plane jaw displacement as a function of applied DC voltage for each of the three mechanical modes of operation. (a) the opening mode, (b) the partial closing mode, and (c)the full closing mode.

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