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TECHNICAL PAPER

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Design and fabrication of an electrothermal microactuator for multi-level conveying

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Abstract During the past years, a variety of microactuators developed for micro-conveyors have been presented. However, such micro-conveyors can only provide conveying motion in a single plane. Here an electrothermally driven microactuator with a capability of adjustable height is proposed, which may act as a basic unit for multi-level conveyors. This microactuator is based on the principle of thermal bimorph actuation with two long conveying fingers to exert out-of-plane bending motions in the transversal direction, which are connected and lifted by an initially curved height adjuster in the longitudinal direction. The devices can provide conveyance of micro-objects between two plane levels of different heights. The testing results show that the two fingers and a height adjuster can be actuated simultaneously and individually with little thermal crosstalk. The proposed device with a dimension of $900 \times 100 \times 4.5\ \mu m^3$ can provide 5 μm vertical displacements by the height adjuster at 1 V and 18 μm lateral displacements by the conveying finger at 2 V. Simulations by finite-element program ANSYS 5.7 have been performed and widely match with testing results.

1 Introduction

The devices in micro-electro-mechanical systems (MEMS) are becoming more versatile and complex in recent years. Among them, micro-conveyors for locomotive mechanisms are one of the key tools to achieve automotive microrobotic systems. In general, microactuators generating large strokes and high forces are neeeded for micro-conveyance applications, and the actuation speed is less important (Fearing 1998). Therefore, arranging microactuators in array configurations to allow the actuators working together becomes a popular approach, which not only can increase the total force and load capacity of the micro-conveyance systems, but also take advantage in MEMS batch fabrication process. Microactuators developed for micro-conveyance systems can be classified into different actuation schemes, such as thermal bimorphs (Ataka et al. 1993), air jets (Konishi and Fujita 1994; Pister et al. 1990), torsional resonators (Mita et al. 1997), electromagnetic (Liu et al. 1995; Nakazawa et al. 1997), piezoelectric (Furuhata et al. 1991), and electrostatic (Edo et al. 1999). The ciliary motion principle proposed by Ataka et al. (1993) used thermal bimorph polyimide legs which were actuated asynchronously to provide propulsion for micro-objects. This ciliary motion system based on thermal-bimorph effect shows simple fabrication process and high load capacity. However, all the reported microactuators for micro-conveyers could only move the micro-objects in a single horizontal plane.

Here an electrothermal microactuator comprising two bimorph fingers with a height adjuster is proposed. Unlike previously reported microactuators in micro-conveyors, the proposed device provides micro-objects conveying not only on the wafer plane but also in vertical direction. The two bimorph fingers can act as the conventional horizontal micro-conveyors unit and the height adjuster can provide an additional moving dimension in vertical direction to form a multilevel micro-conveyor basic unit. For application of micro-warehouse and micro-factory systems, the proposed height adjuster can adjust the heights of the objects to fine-tune the precise positions of these micro-objects. Furthermore, the weights and sizes of micro-objects could be different and hence the objects might be moving on different vertical positions that may increase the difficulties of micro-assembly. Therefore, to assembly the three-dimensional micro-objects, multi-level conveyance provides more degree-of-freedom in control and

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improves the precision of assembly, by controlling the lifting heights of the height adjuster. Especially it could save more space in wafer plane because this micro-conveyor can translate the micro-objects to different heights in a limited area. The design and testing of this basic microactuator unit for multi-level conveyance will be described below.

2 Concept design

The proposed microactuator is composed of two major units, as shown in Fig. 1. One is the height adjuster unit, formed by two bimorph beams in the longitudinal direction with a dimension of 50 μm (La)×10 μm (Wa)×4.5 μm (h) arranged in parallel. The other is the conveying finger unit in the transversal direction, which comprises of two identical bimorph finger structures with a dimension of about 400 μm (Lc)×50 μm (Wc)×4.5 μm (h). The whole device area including connection part of the two units is about 900×100 μm^2 where contact pads are not included. Figure 2 depicts operation principle of the proposed multi-level conveyance to move micro-object from plane 2 (upper plane) to plane 1 (lower plane) with lateral displacement of D and vertical displacements of Δd. Figure 3 shows the layout of the electrical heating resistors. There are four independent close-loops of electrical circuits acting as heating resistors with eight electrical contact pads. Two of them are for the height adjuster, which allows this microactuator to provide vertical motion. Others are for the conveying finger unit to provide the conveying motion. At initial state, the height adjuster and the conveying fingers are bent upward due to the residual stress gradient in two layers of bimorph structures. When the height adjuster unit is heated, the height of the two conveying fingers is adjustable to provide conveying function in different horizontal planes by joule heating two fingers individually or simultaneously.

3 FEM simulation

To perform the simulation of this microactuator, the numerical finite-element program ANSYS 5.7 is used. The half-symmetry 3D model of the microactuator is built and meshed by the Solid5 element type. Solid5 has a three dimensional magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. This element has eight nodes with six degrees of freedom. The bimorph structure comprises a 3-μm-thick polyimide (PIX-L110SX) bottom layer, and an 1.5-μm-thick polyimide (PI2525) top layer. The Cr(40 Å)/Au(1000 Å)/Cr(40 Å) metal layers are embedded between the top and bottom layers acting as the heating resistors. The conveying fingers and the height adjuster of the FEM model are initially curved upward in circular shapes to approximate the actual fabrication results. Figure 4 shows the simulated deformed shape of the microactuator in half-symmetry where only the height adjuster is heated. The physical properties of materials used in simulations are listed in Table 1.

The simulated displacements versus input voltages of the conveying finger and the height adjuster are shown and compared with experimental results in Sect. 5. Simulation results show that the 400-μm-long finger can produce 20-μm displacements at 2 V and the height adjuster with 50 μm length can provide 6 μm downward displacements at 1 V.

4 Fabrication

The microactuator proposed here is batch-fabricated by surface-micromachining technique. The four-mask fabrication process is outlined in Fig. 5. First, the 1-μm-thick aluminum sacrificial layer is deposited by thermal evaporation. Then it is patterned to form the anchor by

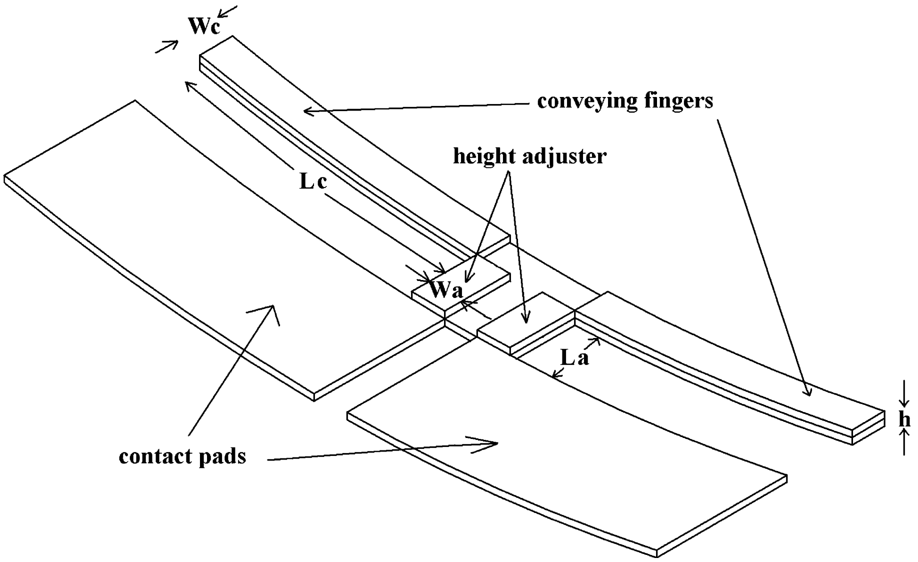


Fig. 1 Schematic drawing of the proposed microactuator

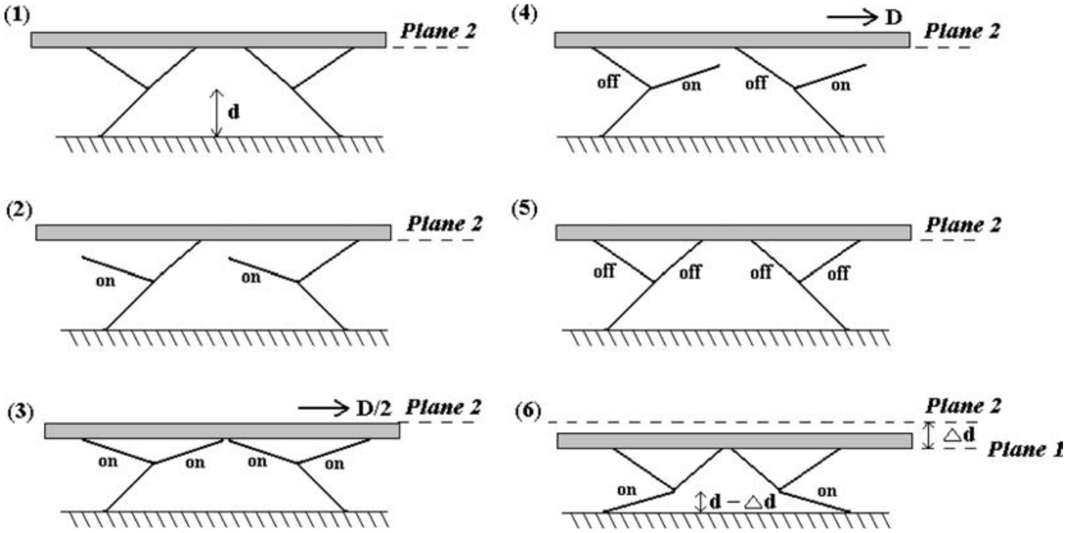
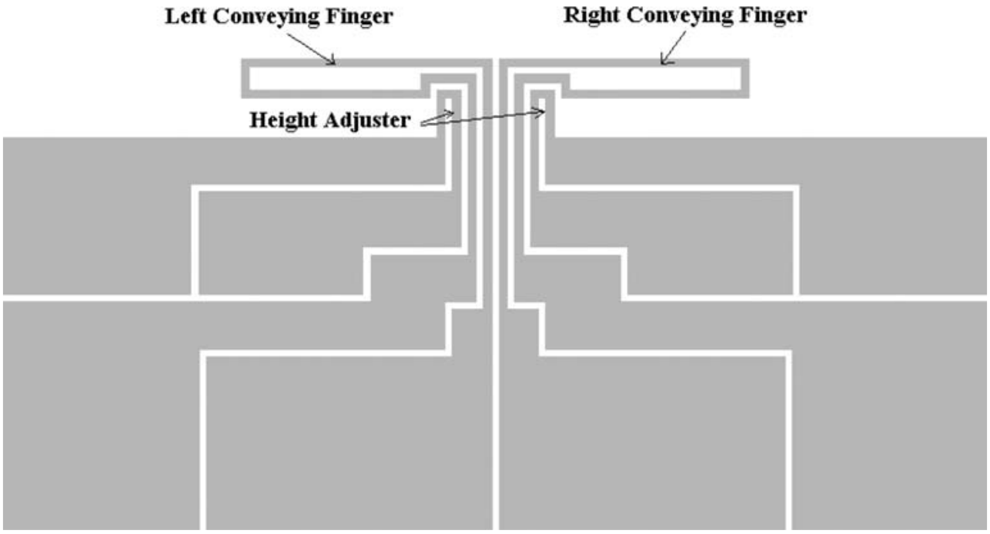


Fig. 2 Operation principle of the proposed multi-level conveyor

Fig. 3 The heater circuit layout of the device



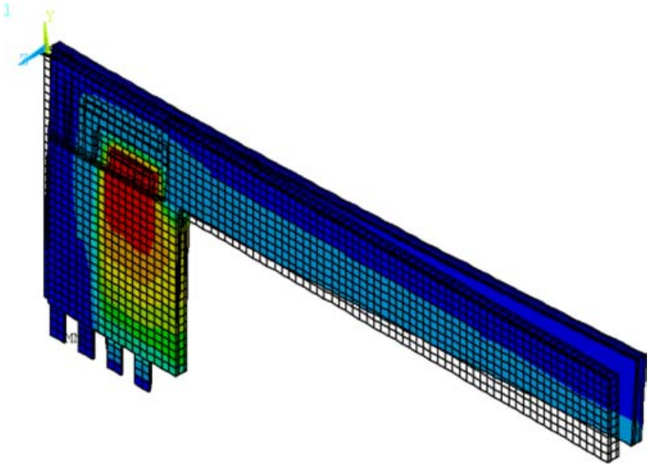


Fig. 4 The simulated deformed shape of the microactuator

mask 1 (Fig. 5a). Polyimide (PIX-L110SX) of 3 μm thickness with lower thermal expansion coefficient is spun coated and cured as the bottom layer of the bimorph structure. Metallic microheater (Cr(40 Å)/Au(1000 Å)/Cr(40 Å)) is formed by lift-off process with mask 2, as shown in Fig. 5b. The Cr layer is used to enhance the adhesion between the Au and polyimide. After that, an 1,000-Å-thick nickel is deposited and patterned by mask 3 to protect the microheater of the height adjuster in the following RIE (Reactive Ion Etching) process (Fig. 5c). On top of them, the 1.5-μm-thick polyimide (PI2525) as the top layer with higher thermal expansion coefficient is coated and cured. Following, an 1,000-Å-thick nickel is evaporated and patterned by mask 4 as hard mask, as shown in Fig. 5d. The top and bottom polyimide layers are then patterned by RIE using oxygen gas.

Table 1 Material properties used in simulations

	Polyimide PIX-L110SX	Polyimide PI2525	Au
Young's modulus (GPa)	8.5	2.5	80
CTE (coefficient of thermal expansion, 1e-6/°C)	10	40	14.3
Thermal conductivity (W/m K)	0.167	0.167	318
Electrical resistivity (Ω–m)	1e14	1e14	23.5e-9

The releasing process is performed by immersing the wafer in aluminum etchant for 10 min, rinsing in DI (deionized) water for 5 min and in IPA (Isopropyl Alcohol) for 30 min to reduce stiction problem sequentially. Then, the device is placed on a hotplate at 110°C for 5 min to suspend the microactuator, as shown in Fig. 5e.

5 Results and discussions

The perspective view and close-up view of the fabricated microactuators are shown in Fig. 6a and b, respectively. It is observed that the ends of the conveying finger and the height adjuster are curled up about 18 and 5 μm from the substrate, respectively, due to the residual stresses in bimorph beams. In testing, various dc voltages are applied to the contact pads to generate different actuation modes. The displacements at the beam ends are measured by focus or defocus method under the optical microscope, which gives a resolution about 1 μm.

Figure 7 shows comparison of the simulation and testing results of the fingertip displacements under various input voltages. In testing, the downward displacement up to 18 μm is achieved at an input voltage of 2 V. The maximum deviation between simulation and testing results is within 10%. In addition, the simulation and testing results of the height adjuster are shown in Fig. 8. In testing, 5 μm downward displacement is achieved at 1 V before touching the substrate, and the deviation between the simulation and measurement results is within 20%. The approximate maximum load per microactuator is about 0.196 mg., which is estimated by calculating the elastic-mechanical stiffness of the adjuster or fingers structures. According to experimental results, the lateral displacement of the conveying finger at output vertical displacement of 13–15 μm is about 0.2–0.3 μm. Hence, the estimated maximum velocity for conveyance is about 1.0–1.5 μm/s at a maximum operating frequency of 5 Hz.

Further, thermal coupling effects of the height adjuster and the conveying fingers are examined by multi-dimensional motion testing. First, the height adjuster is actuated at 1 V, and then different voltages are applied to the conveying fingers to observe whether the conveying finger is affected by the height adjuster. The height adjuster deflects 5 μm in downward direction at 1 V while the conveyor fingers are not actuated. Figure 9 shows the measured displacements of the height adjuster at 1 V while applying different voltages to the conveying fingers simultaneously. As shown in Fig. 9, the deviations on positions of height adjuster end are negligible and that all are within a measurement resolution of 1 μm. It is also found that the tips of conveying fingers deflect 18 μm at 2 V, while the height adjuster still delivers 5 μm downward displacement at 1 V. Testing results indicate that the displacements of height adjuster are not affected by operating conveying fingers. Similar testing processes are also performed to the

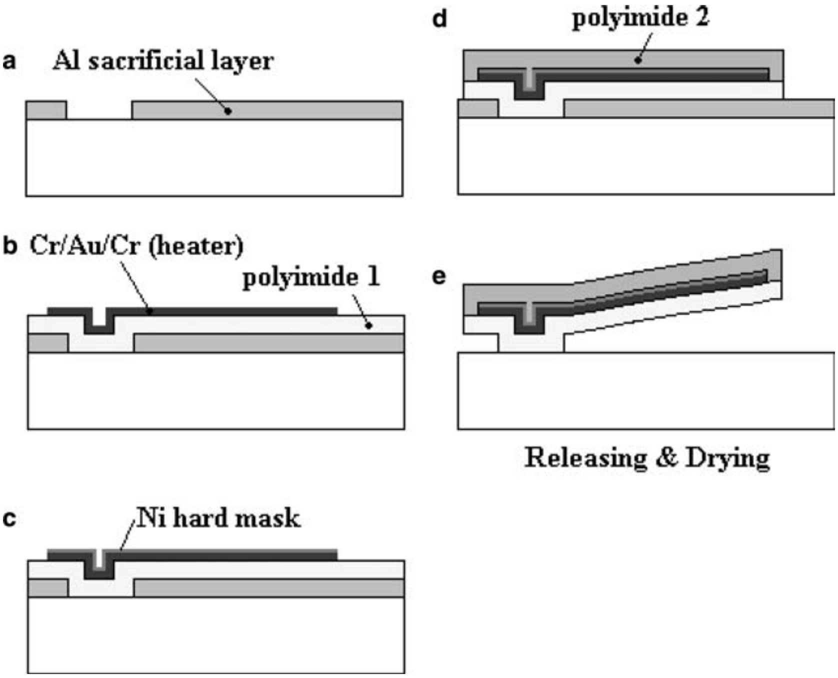


Fig. 5 Fabrication process

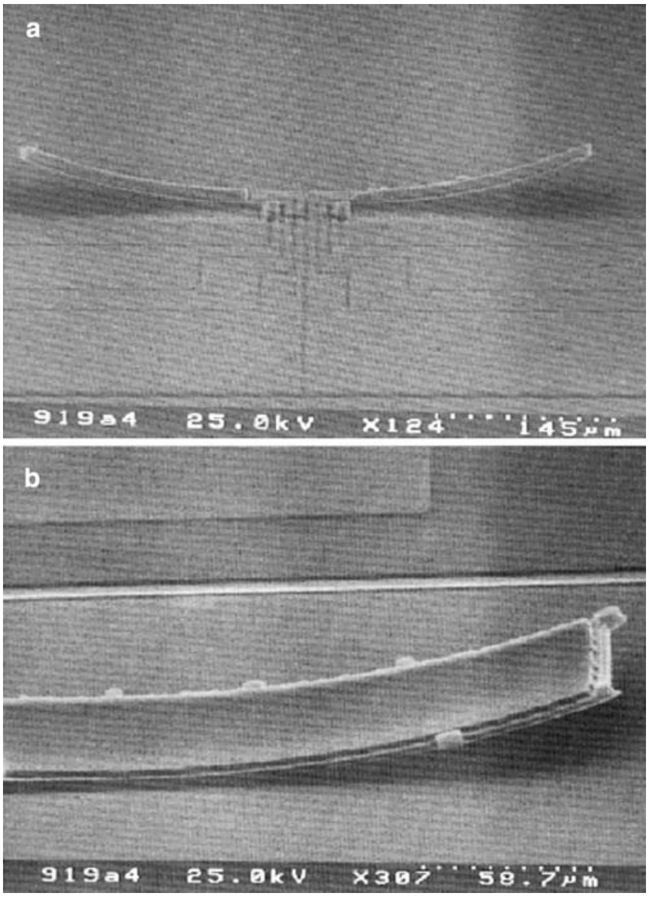


Fig. 6 Scanning electron microscopes of the fabrication results. **a** Perspective view of the device, and **b** close-up view of the finger

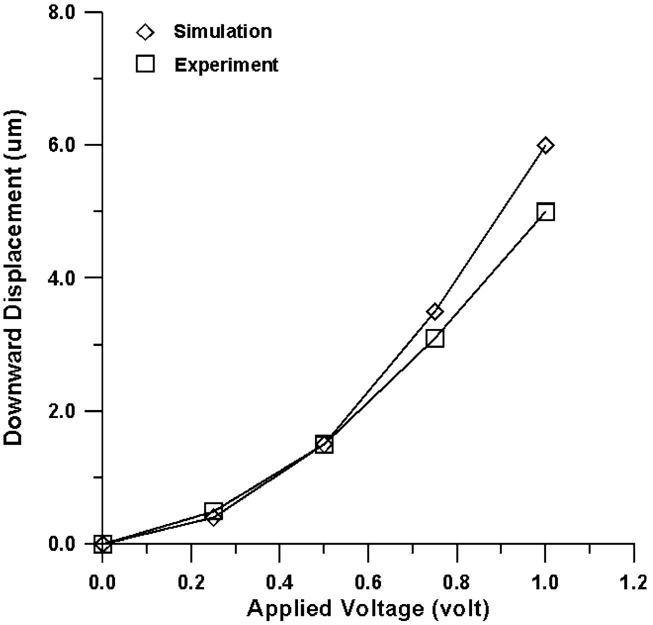


Fig. 8 The simulated and calibrated downward displacement of the height adjuster under different input dc voltages

conveying fingers. Figure 10 shows the load-position curves of the conveying fingertip with simultaneous actuation of height adjuster. Different curves in Fig. 10 represent different dc driving voltages of the height adjuster. From this testing, it is observed that the downward deflection of the conveying fingertip relative to the end of the height adjuster is affected by the actuation of height adjuster slightly. For instance, the downward displacements of the conveying finger actuated at 1.5 V with the height adjuster actuated at 0.75 and 0 V are

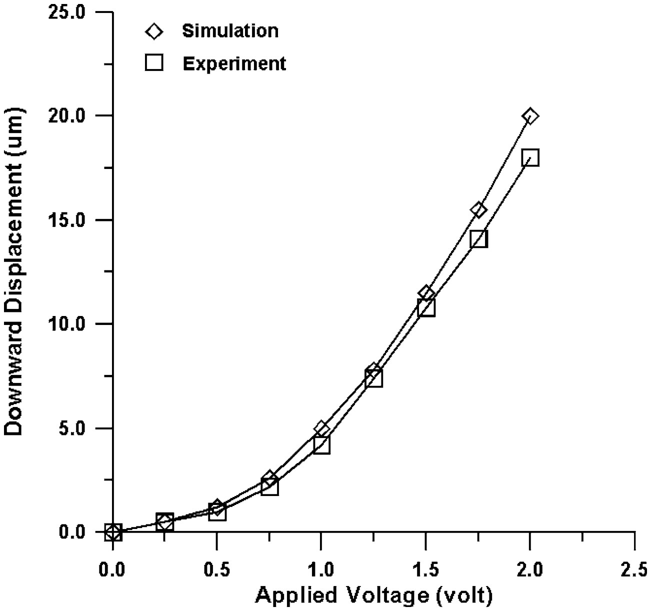


Fig. 7 The simulated and calibrated downward displacements of the conveying finger under different input dc voltages

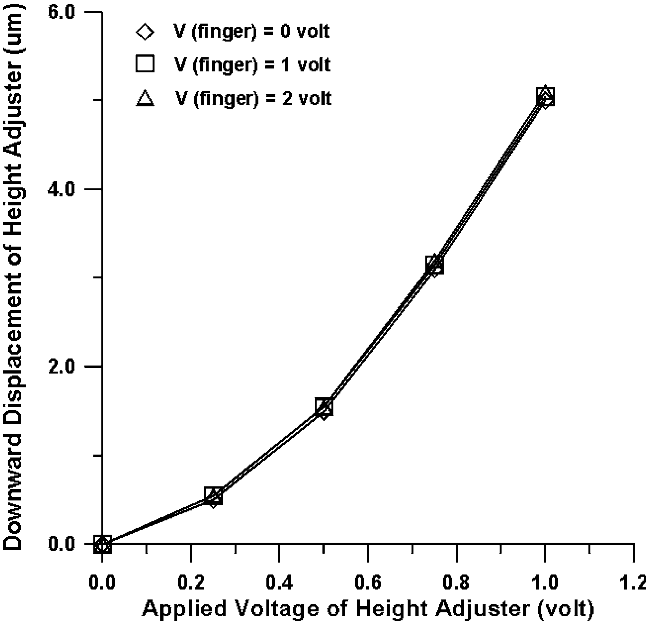


Fig. 9 The measured displacements of the height adjuster in thermal coupling test

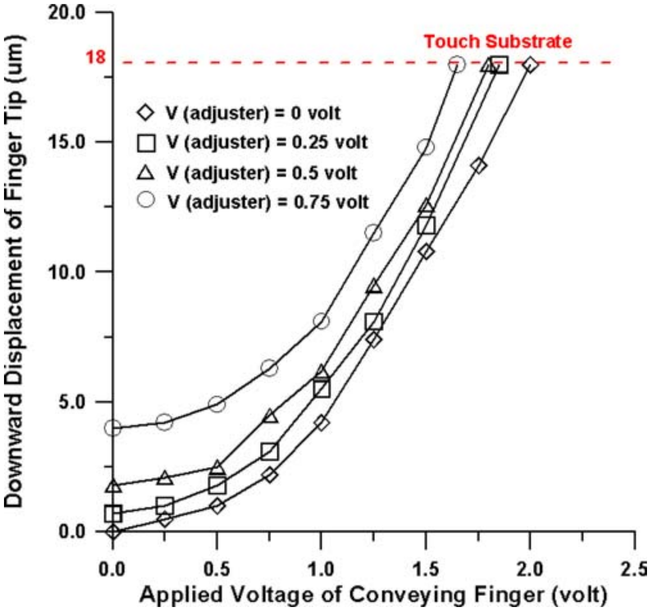


Fig. 10 The measured displacements of the fingertip in thermal coupling test

14.5 and 10.5 μm respectively. However, the height adjuster produces about 3 μm downward displacement at 0.75 V. Hence, the absolute downward displacement of conveying finger affected by thermal crosstalk from height adjuster is actually around 1 μm. In testing, the increased downward displacements of conveying finger are all below 10% of the displacements without actuating the height adjuster.

6 Conclusion

An electrothermally driven microactuator for multi-level conveyance is designed, simulated, fabricated, and tested. Besides the conventional horizontal conveying, a height adjuster is included to enhance the conveying range from single-plane to multi-level conveying. It is also shown that the proposed device can be operated at input voltage below 3 V. The simulation results agree with the test results. From thermal coupling tests, this device is shown to have little cross talking while heating the height adjuster and the two conveying fingers. It means the height adjuster and two fingers can be operated almost independently. The material selections and dimension designs of this microactuator can be further investigated to improve the performance.

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