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Digital Control of Active Network Microstructures on Silicon Wafers

Zhongjing Ren, Jianping Yuan and Peng Yan

Abstract

This chapter presents a promising digital control of active microstructures developed and tested on silicon chips by current division and thus independent Joule heating powers, especially for planar submillimeter two-dimensional (2-D) grid microstructures built on silicon wafers by surface microfabrication. Current division on such 2-D grid networks with 2×2 , 3×3 , and $n \times n$ loops was modeled and analyzed theoretically by employing Kirchhoff's voltage law (KVL) and Kirchhoff's current law (KCL), which demonstrated the feasibility of active control of the networks by Joule heating effect. Furthermore, *in situ* testing of a typical 2-D microstructure with 2×2 loops by different DC sources was carried out, and the thermomechanical deformation due to Joule heating was recorded. As a result, active control of the current division has been proven to be a reliable and efficient approach to achieving the digital actuation of 2-D microstructures on silicon chips. Digital control of such microstructural networks on silicon chips envisions great potential applications in active reconfigurable buses for microrobots and flexible electronics.

Keywords: surface microfabrication, current division, joule heating, digital control, grid microstructures

1. Introduction

Silicon-based microelectromechanical systems (MEMS) devices, including sensors, actuators, and generators, show wide applications in microrobots [1], medical devices [2, 3], and flexible electronics [4]. Such miniaturized systems, on one hand, offer great potentials for improving the abilities of micromanipulation and functioning in some extreme conditions, such as limited working space and large displacements; On the other hand, however, the strong requirement of precise and effective control of these kinds of devices is not easy. Therefore, microstructures allowing for reliable and efficient actuation and large displacement are worth investigating.

Thermal microactuators have been proven to be able to realize large displacements more efficiently, and a variety of materials, for example, ceramics [5–7], polymers [8], composites [1, 9, 10], and metals [11–14], are available for building such active microstructures. Moreover, the geometries of these microstructures heavily depend on the selected materials, among which electrothermal bilayer beams have obvious advantages on large displacements, low costs, and high compatibility with mature microfabrication processes. Many efforts have been paid to

develop electrothermal microstructures based on different applications and requirements. A safety and arming device composed of two V-shape electrothermal actuators was built, and the design of a cascaded V-beam amplification and two mechanical sliders enabled large deformation. As a result, a large planar displacement of $231.78\text{ }\mu\text{m}$ was achieved by applying a voltage of 15 V [15]. A typical U-shape electrothermal actuator made of a single material allowing for planar bending due to the thermal mismatch between the cold and hot arms was developed. Since the Joule heating power on the narrower arm was smaller than the wider one, the thermal expansion on the narrower (or hot) arm is larger than that of the wider (or cold) arm [16]. Another representative study is related to high frequency, low power, electrothermal bimorph actuators with shape memory effects, and the significant thermal mismatch and shape memory effect contributed to very large out-of-plane deformation [17].

However, previous research on electrothermal actuators usually focused on development beams with simple geometries, such as bridges, V-shape, U-shape, etc. The current flows through the beams were the same, which limited their ability of reconfiguration. To accomplish diverse reconfiguration of such electrothermal microstructures, active current division across planar (or 2-D) bilayer microstructures offers a promising approach to digital control of microstructures for distributed thermal balance and thus various deformations.

Our group has been endeavoring to design, fabrication, and characterization of 2-D multilayered microstructure consisting of beams for out-of-plane deflection, vertical deployment [18–24], and twisting under electrothermal actuation [9]. These microstructures can be created on whole wafers and tested separately by cutting the silicon wafer into chip-scale pieces [18]. Active parts of such microstructures are released by selective etching on the silicon substrates, while the anchored parts are protected from being etched. Different Joule heating powers and balanced temperatures on the grid networks could be obtained. However, instead of qualitative analysis, it is more important and meaningful to quantify the effect of electrothermal effect of bilayer 2-D microstructures, which will lay a solid foundation for modeling and predicting their potentials for large out-of-plane displacement.

The rest of this chapter is organized as follows. In Section 2, theoretical analysis of current divisions in some typical 2-D grid microstructures is firstly carried out, followed by the quantitative analysis of the equivalent resistance and Joule heating power. After that, fabrication and characterization of electrothermal and thermomechanical performances are presented experimentally in Section 3. The results are then shown and discussed in Section 4. Finally, the chapter is concluded in Section 5.

2. Theoretical analysis of current divisions

In this section, Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) are employed appropriately to figure out the feasible current division in several representative 2-D grid structures. Note that the scale of the 2-D structures does not change the relative division ratios between these beams. So, we consider more general structures, instead of only microstructures, in this section. It also hints that such cross-scale research on the current distribution is applicable to multiple surroundings and uses. For the sake of simplicity, all the grid structures presented in this chapter are composed of bilayer beams with the same materials and dimensions. Furthermore, these beams are incorporated into grid networks with different geometries. Two representative 2-D grid structures with the 2×2 loops and 3×3 loops are shown in **Figure 1**, where the candidate input ports are marked as red dots. The 2×2 grid structure consists of 12 beams for the current division, while the

Figure 1.
Schematic views of two planar grid structures for the current division.

3×3 one consists of 24 beams. Besides that, it is worth noting that grid structures with $n \times n$ loops can be similarly proven to be made of $2n(n + 1)$ beams.

Let us start with studying the current division through 2×2 grid structures by assuming that a constant voltage V is applied to any two outer red nodes, as seen in **Figure 1**. To ensure the stable connection between the voltage source and the red input nodes, another two supporting beams with fixed ends anchored on silicon wafers are designed. Hence, it can be derived simply that there are six independent cases in total for voltage inputs, as illustrated in **Figure 2**. The resistances of the beams in grid structures, as well as those of the two supporting beams, are assumed to be the same R . To acquire the current distribution through these beams of all the cases, KCL and KVL are adopted to the nodes and loops, respectively. Taking Case 1 as an example, as presented in **Figure 3**, nine independent KCL equations at the nodes N_i ($i = 1, 2, \dots, 9$) and five independent KVL ones at the loops C_i ($i = 1, 2, \dots, 5$) are established, as shown in Eq. [1].

Specifically, the KCL equations could be written as

$$\begin{cases} I_1 - I_2 - I_4 = 0 \\ I_2 - I_3 - I_5 = 0 \\ I_3 - I_6 = 0 \\ I_4 - I_7 + I_8 + I_{10} = 0 \\ I_5 - I_8 + I_9 - I_{11} = 0 \\ I_6 - I_9 - I_{12} = 0 \\ -I_{10} + I_{13} = 0 \\ I_{11} - I_{13} + I_{14} = 0 \\ I_{12} - I_{14} = 0 \end{cases} \quad (1)$$

while the KVL equations are formulated as

$$\begin{cases} V - (I_1 + I_4 + I_7) \cdot R = 0 \\ I_4 \cdot R - (I_2 + I_5 + I_8) \cdot R = 0 \\ I_5 \cdot R - (I_3 + I_6 + I_9) \cdot R = 0 \\ I_8 \cdot R - (I_{10} + I_{11} + I_{13}) \cdot R = 0 \\ (I_9 + I_{11}) \cdot R - (I_{12} + I_{14}) \cdot R = 0 \end{cases} \quad (2)$$

As a result, the 14 unknowns I_i ($i = 1, 2, \dots, 14$) can be uniquely solved by the derived 14 independent equations, that is,

Figure 2. Six independent cases of voltage inputs into grid structures with 2×2 loops. The red arrows denote the current directions, while the red numbers represent the current division factors between different beams in each case. Note that factors of beams without current flow are 0.

Figure 3. KCL and KVL on case 1 of the grid structures with 2×2 loops and two supporting beams.

$$\left\{ \begin{array}{l} I_1 = I_7 = \frac{24}{65} \cdot \frac{V}{R} \\ I_2 = \frac{7}{65} \cdot \frac{V}{R} \\ I_3 = I_6 = I_{10} = I_{13} = \frac{2}{65} \cdot \frac{V}{R} \\ I_4 = \frac{17}{65} \cdot \frac{V}{R} \\ I_5 = I_8 = \frac{5}{65} \cdot \frac{V}{R} \\ I_9 = I_{11} = I_{12} = I_{14} = \frac{1}{65} \cdot \frac{V}{R} \end{array} \right. \quad (3)$$

which demonstrates the determination of current division factors for all the beams in Case 1. Similarly, the current division factors in Cases 2–6 can be obtained uniquely, as seen in **Figure 2**.

Further investigation on the current distribution across planar structures with 3×3 loops was taken, and the division factors and directions of the current flows had been proved to be unique. Generally, there are 12 independent cases for voltage inputs, as seen in **Figure 4**. Particularly, current distributions of two representative geometries with 3×3 loops, Case 3 and Case 6, are solved and illustrated in **Figure 5**. A very interesting phenomenon observed in Case 3 of the 3×3 loops structure is that the current division factors are symmetric about the central axis marked as a green dashed line in **Figure 5**. Further exploration reveals that the

Figure 4.
Twelve independent cases of voltage inputs into grid structures with 3×3 loops.

Figure 5.
Current distributions of two representative cases of voltage inputs into grid structures with 3×3 loops.

Figure 6.
Current distribution across an $n \times n$ loops geometry like Case 6 in Figure 5.

directions of current flows symmetrical about the green line are opposite, and the magnitudes of the currents closer to the input ports tend to be larger. In addition, though the distribution regularity of Case 6 is a little more complicated than that of

Figure 7.
SEM image of a representative 2-D microstructure consisting of bilayer beams.

the Case 3, a very interesting symmetric current distribution about the diagonal of the geometry is found. Similarly, current flows through more complex geometries with $n \times n$ loops like Case 6 are shown in **Figures 6** and **7**. It is worth noting that the corresponding current division factors in **Figure 6** are represented by E_i ($E_2 = 2E_1$, $E_n = E_{n-1} + E_{n-2}$ when $n \geq 3$ and n is odd, $E_n = (E_{n-1} + E_{n-2})/2$ when $n \geq 3$ and n is even). Generally, there are $(2n - 2)$ different currents through the $n \times n$ grid network, enabling digital control of diverse and regional Joule heating powers across such a 2-D network.

Based on the current divisions of 2×2 loops structures with diverse voltage inputs' cases presented and discussed in this section, the effect of Joule heating on such conductive grid structures is available to be quantified and evaluated.

Assuming that the resistances of a single beam in the 2×2 loops, as well as each of the supporting beams, are the same, R , and the external voltages applied are V , The equivalent resistances of each case of the 2×2 grid structures shown in **Figure 2** can be solved using KCL and KVL laws, which was presented in the previous research. The Joule heating power of the grid structures and supporting beams can be then determined and listed in **Table 1**, where R_i represents the resistance in case i , while the P_i represents the heating power when a voltage of V applied. It can be seen clearly from **Table 1** that equivalent resistances are approximately three times over the resistance of a single beam, and thus the expected Joule heating power is about one-third of the power when a single beam is applied by a voltage of V .

Similarly, the equivalent resistances of the 3×3 loops structure in Case 3 and Case 6 can be derived to be $293/56 \cdot R$ and $27/7 \cdot R$, respectively.

Case (i)	1	2	3	4	5	6
Equivalent Resistance (R)	65/24	13/4	77/24	7/2	3	17/6
Heating Power (V^2/R)	24/65	4/13	24/77	2/7	1/3	6/17

Table 1.
Equivalent resistances and joule heating powers of the six cases of 2×2 loops with two supporting beams.

3. Experimental validation of 2-D microstructures

3.1 Fabrication of 2-D grid microstructures

To demonstrate the effect of electrothermal actuation of the 2-D structures, a series of ultrathin (or 2-D) microstructures consisting of grid beams and supporting beams that are mentioned in Section 2 are designed, fabricated, and tested.

Several previous research by our group can be referred to on a typical design and fabrication processes of such 2-D microstructures with two different materials. Specifically, aluminum and NiTi alloys (which are in the austenite phase in the range of testing temperatures) are selected as the bottom layer and top layer, respectively. What needs to be emphasized here is that although NiTi alloys show great potential for shape memory effects, this effect is not introduced intentionally in this research. It is the effect of digital Joule heating that we want to present in this chapter. Aluminum was chosen due to its significantly larger coefficient of thermal expansion than that of the NiTi alloys in the austenite phase.

As a result, a typical 2-D microstructure with the geometry presented in **Figure 3** was imaged by the SEM after being selectively released from the silicon chip, as seen in **Figure 7**. It is worth noting that these two contact pads attached to the silicon chip were connected to gold wires with a diameter of 20 μm . The gold wire was used for electrical signal transfer from the logic printed circuit board after being fixed on the *in situ* imaging stage in SEM.

3.2 Results and discussion of *in situ* test of the microstructure

The experimental setup for *in situ* electrothermal actuation of the microstructure is illustrated in **Figure 8**. The stage of the SEM was tilted from zero degree to 45 degree for easier observation and measurement, and the configuration of the microstructure without heating was reimaged as shown in **Figure 9**. The *in situ* electrothermal testing of such a microstructure on the silicon chip started with the

Figure 8.
Experimental setup of microstructures on the silicon chip for testing.

Figure 9.
SEM image of the microstructure after being tilted by 45 degrees.

Figure 10.
SEM images of microstructures under different driving voltages in electrothermal testing.

application of a DC source by the Agilent 4155C Semiconductor Parameter Analyzer. The shapes of the microstructure under constant voltages of 12 mV, 15 mV, 18 mV, and 19 mV were imaged and presented in **Figure 10**, and a supplementary

video about this process was recorded simultaneously. It can be seen from **Figure 10**, as well as the video, that the microstructure could be digitally actuated by distributed currents for diverse and regional Joule heating. Therefore, the effect of active control of microstructures using digitally distributed currents is demonstrated. It is important to highlight that although the “digital currents” were inherently ensured, the thermomechanical reconfiguration of corresponding beams does not seem to be that “digital”. It could be explained by the effect of scaling which could have a significant influence on the thermal conduction between the beams. The scaling effect is expected to be alleviated gradually with structural scale-up. Generally, such silicon chip-based microfabrication processes show great compatibility, effectivity, and efficiency in the development and validation of 2-D microstructures.

4. Conclusions

In conclusion, effective and efficient development of active control of 2-D microstructures based on silicon chips is presented in this chapter. Representative planar structures composed of grid beams are introduced to quantitatively analyze possible current distribution across the conductive geometry using KCL and KVL. Diverse current divisions of structures with different loops and voltage inputs have been proven to be available for digital control of electrothermal actuators. Besides that, the determination of equivalent resistances and resulting Joule heating powers have contributed to the evaluation of *in situ* experiments on the representative microstructure created on silicon chips by microfabrication. The process and critical steps of thermomechanical deformation of such a microstructure are shown to demonstrate the effect of digital control by Joule heating. The insignificant digital deformation could be attributed to the scale effect of thermal conduction.

It is worth highlighting that much more various and precise current divisions can be obtained by superposition of different voltage inputs, which can be an attractive topic in the future. Another promising research is to investigate the scale effect on Joule heating in different current distributions.

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Conflict of interest

The authors declare no conflict of interest.

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References

- [1] Su X, Ren Z, Yan J, Shi Y, Pan Q. Microstructure and twisting ability of an adjusted antisymmetric angle ply laminate. *Applied Physics Letters*. 2019; **114**(21):211902. DOI: 10.1063/1.5089809
- [2] Chun YJ, Levi DS, Mohanchandra KP, Fishbein MC, Carman GP. Novel micro-patterning processes for thin film NiTi vascular devices. *Smart Materials and Structures*. 2010; **19**(10):105021. DOI: 10.1088/0964-1726/19/10/105021
- [3] Ghazali FAM, Hasan MN, Rehman T, Nafea M, Ali MSM, Takahata K. Micro-electromechanical-system actuators for biomedical applications: A review. *Journal of Micromechanics and Microengineering*. 2020; **30**(7):073001. DOI: 10.1088/1361-6439/ab8832
- [4] Kamyshny A, Magdassi S. Conductive nanomaterials for 2D and 3D printed flexible electronics. *Chemical Society Reviews*. 2019; **48**(6): 1712-1740. DOI: 10.1039/C8CS00738A
- [5] Galos R, Shi Y, Ren Z, Zhou L, Sun H, Su X, et al. Electrical impedance measurements of PZT nanofiber sensors. *Journal of Nanomaterials*. 2017; **2017**(Special Issue):8275139. DOI: 10.1115/DETC2016-59687
- [6] Galos R, Shi Y, Ren Z, Synowicki R, Sun H, Nykypanchuk D, et al. The dielectric constant of PZT nanofiber at visible and NIR wavelengths. *Nano-Structures and Nano-Objects*. 2018; **15**: 205-211. DOI: 10.1016/j.nanos.2017.10.001
- [7] Galos R, Shi Y, Ren Z, Sun H. Electrical impedance matching of PZT nanogenerators. In: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*; 6–9 August 2017; Cleveland, Ohio, USA. p. 47 V004T09A025
- [8] Al-Zandi MH, Wang C, Voicu R, Muller R. Measurement and characterisation of displacement and temperature of polymer based electrothermal microgrippers. *Microsystem Technologies*. 2018; **24**(1): 379-387. DOI: 10.1007/s00542-017-3298-8
- [9] Su X, Ren Z, Sun H, Shi Y, Pan Q. The submicron fabrication process for T gate with a flat head. In: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*; 26–29 August 2018; Quebec City, Quebec, Canada. p. V004T08A018
- [10] Su X, Ren Z, Pan Q, Lu M, Camino F, Shi Y. Design, modeling and experimental validation of a micro cantilever beam with an electro-controllable twisting ability. *Journal of Micromechanics and Microengineering* 2021; **31**(6):065010. DIO: 10.1088/1361-6439/abfc35
- [11] Sun H, Luo J, Ren Z, Lu M, Shi Y. Effects of deposition and annealing conditions on the crystallization of NiTi thin films by e-beam evaporation. *Micro and Nano Letters*. 2020; **15**(10):670-673. DIO: 10.1049/mnl.2020.0004
- [12] Sun H, Luo J, Ren Z, Lu M, Nykypanchuk D, Mangla S, et al. Shape memory alloy bimorph microactuators by lift-off process. *Journal of Micro and Nano-Manufacturing*. 2020; **8**(3): 031003. DOI: 10.1115/1.4048146
- [13] Ren Z, Yuan J, Su X, Sun H, Galos R, Shi Y. A new fabrication process for microstructures with high area-to-mass ratios by stiffness enhancement. In: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*; 26–29 August 2018; Quebec City, Quebec, Canada. p. V004T08A034

- [14] Ren Z, Yuan J, Su X, Sun H, Galos R, Shi Y, et al. Vertical deployment of multilayered metallic microstructures with high area-to-mass ratios by thermal actuation. *Journal of Micro and Nano-Manufacturing*. 2019;7(3):031002. DOI: 10.1115/1.4043987
- [15] Li X, Zhao Y, Hu T, Xu W, Zhao Y, Bai Y, et al. Design of a large displacement thermal actuator with a cascaded V-beam amplification for MEMS safety-and-arming devices. *Microsystem Technologies*. 2015;21(11):2367-2374. DOI: 10.1007/s00542-015-2447-1
- [16] Hussein H, Tahhan A, Le Moal P, Bourbon G, Haddab Y, Lutz P. Dynamic electro-thermo-mechanical modelling of a U-shaped electro-thermal actuator. *Journal of Micromechanics and Microengineering* 2016;26(2):025010. DOI: 10.1088/0960-1317/26/2/025010
- [17] Knick CR, Sharar DJ, Wilson AA, Smith GL, Morris CJ, Bruck HA. High frequency, low power, electrically actuated shape memory alloy MEMS bimorph thermal actuators. *Journal of Micromechanics and Microengineering* 2019;29(7):075005. DOI: 10.1088/1361-6439/ab1633
- [18] Ren Z. Design, fabrication, and control of reconfigurable active microstructures for solar sails [thesis]. Stevens Institute of Technology; 2020
- [19] Ren Z, Yuan J, Shi Y. Electro-thermo-mechanical modelling of micro solar sails of chip scale spacecraft in space. *Microsystem Technologies*. 2021;27(12):4209-4215. DOI: 10.1007/s00542-020-05204-x
- [20] Ren Z, Yuan J, Su X, Bauer R, Xu Y, Mangla S, et al. Current divisions and distributed Joule heating of two-dimensional grid microstructures. *Microsystem Technologies*. 2021;27(9):3339-3347. DOI: 10.1007/s00542-020-05103-1
- [21] Ren Z, Yuan J, Su X, Mangla S, Nam C-Y, Lu M, et al. Thermo-mechanical modeling and experimental validation for multilayered metallic microstructures. *Microsystem Technologies*. 2021;27(7):2579-2587. DOI: 10.1007/s00542-020-04988-2
- [22] Ren Z, Yuan J, Su X, Mangla S, Nam C-Y, Lu M, et al. Electro-thermal modeling and experimental validation for multilayered metallic microstructures. *Microsystem Technologies*. 2021;27(5):2041-2048. DOI: 10.1007/s00542-020-04964-w
- [23] Ren Z, Yuan J, Su X, Shi Y. A novel design and thermal analysis of micro solar sails for solar sailing with chip scale spacecraft. *Microsystem Technologies*. 2021;27(7):2615-2622. DOI: 10.1007/s00542-020-05094-z
- [24] Ren Z, Yuan J, Su X, Xu Y, Bauer R, Mangla S, et al. Multilayered microstructures with shape memory effects for vertical deployment. *Microsystem Technologies*. 2021;27(9):3325-3332. DOI: 10.1007/s00542-020-05101-3