Al/Ti-film-resistor based thermal heater with Zig-Zag configuration for MEMS application

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Abstract. In this paper, we proposed a micro-heater based on Al/Ti-film resistors for MEMS application. The film heater, designed with unique Zig-Zag configuration, has a high heating efficiency as generated Joule heat could be confined in Zig-Zag area. Consequently, much higher maximum temperature could be achieved under the lower applied voltage, compared with conventional strategy. Based on MEMS technique, thin film based micro-heater was fabricated, and experimental characterization was carried out in room temperature. Since the micro-heaters are all in the form of thin film-resistors, the structure design is simple and fabrication process compatibility is good, which is particularly suitable in the fields of MEMS integration and actuation application.

1. Introduction
In the past decades, micro-heaters have been extensively investigated and found wide application in MEMS sensors and actuators, e.g. gas sensor, thermal actuator and thermal flow sensor [1, 2]. In our previous work, we proposed an original out-of-plane micro-force function generator to achieve accurate modifying of micro deformation for MEMS devices [3, 4]. General requirements for thin film micro heater are low power consumption, fast response, good heat confinement, good mechanical stability, and good fabrication yield [5, 6]. One obvious advantage of the electro-thermal actuators is that it can provide large force and displacements at CMOS comparative voltage/current, and thus it could be easily for incorporation with other MEMS structures [7, 8]. The thermal actuators were fabricated utilizing polymeric SU-8 as the main functional material and thin film as the micro heater [3, 9, 10].

In this paper, we will give detailed introduction of the film-resistor based thermal heater with Zig-Zag configuration for thermal actuation application. Batch fabrication process of the film-resistor will be mentioned, as well as basic characterization of the fabricated thermal heater will also be carried out.

2. Design and fabrication
Thermal actuation has advantages over other types of strategies, which features compactness, high force, and low driving voltage. There are mainly two types of micro-heaters, including wire-heater and film-heater. Due to the lower heat mass, ease of integration and compatibility, the thin-film micro heaters have more interesting applications than wire ones. Here, we choose metal Ti as the resistor layer due to the high resistivity and good adhesion with substrate, while metal Al as the conductive layer as for its low resistivity which can be used as electrode for wire bonding.
2.1. Design and analysis
Conventionally, structure configuration could obviously affect heating efficiency and induce heat loss. We have compared two different types of film-heaters based on ANSYS software, as shown in Figure 1. When DC current applied to micro-heater, the generated Joule heat is efficiently transferred to the surrounding environment through interfaces. We can find that in the design of Option B in Figure 1, the heat is concentrated in the effective working Zig-Zag area, and the maximum temperature of the heater is obvious higher than Option A. Finite element software ANSYS was used to simulate the performance of the proposed electro-thermal heater. Material properties used in the electro-thermal coupled analysis are summarized in Table 1.

Simulation results showed maximum temperature of two different heaters, which follows an exponential trend with applied voltage, as shown in Figure 2. Maximum temperature of the micro-heater with Al/Ti configuration could be as high as ~730K, which was significantly higher than single Ti configuration. Since Al metal is used as conductive layer and lead electrode, the temperature field distribution of the Al/Ti thin film heater is obviously concentrated in the middle Zig-Zag zone. In order to simplify simulation process in our analysis, the main approach of energy loss of micro heater is heat
conduction through glass substrate due to the small size, while effects of thermal radiation and thermal convection were not taken into consideration in simulation.

| Material Property                  | Glass | Ti  | Al  |
|------------------------------------|-------|-----|-----|
| Young's Modulus (Gpa)              | 70    | 96  | 69  |
| Poisson's ratio                    | 0.22  | 0.35| 0.33|
| Thermal conductivity (W/mk)        | 3.2   | 5.76| 237 |
| Resistivity (Ω/cm)                | 1.18  | 1.7 | 0.03|
| Coefficient of Thermal Expansion (ppm/K) | 1.26  | 23.1| 9.4 |

2.2. Fabrication

In our fabrication process, Pyrex glass with thickness of 500μm was selected as the bulk substrate, due to low thermal conductivity and high electrical resistivity, and consequently could realize good heat confinement and lower power consumption. Film resistors, consisted of Ti/Al bi-layer films, were adhered to the insulated glass substrate. On the premise of fully guaranteeing the thin film electrode process yield and heating efficiency, the Zig-Zag region was designed with line width of 50μm, while the gap distance is 25μm, as shown in Figure 3. The thickness of metal film plays an important role on the efficiency of the heater, and electrical parameters of the metal thin film showed a large fluctuation with the processing process.

Figure 3. Layout of designed Al/Ti micro-heater and the key parameters.

In order to analyze the relationship between resistance value and film thickness, two types of film resistors with different thickness were fabricated. First, in Figure 4a,b, a layer of metal Ti with thickness of 200nm and 600nm was separately deposited on glass substrate by sputtering, and then a thin layer of metal Al film with thickness of 70 nm was deposited on the top of above Ti layer. Then positive photoresist was spin coated onto the metal layers and patterned using photolithography, with a pre-designed MASK-I to form the Al conductor pad, as shown in Figure 4c. After that, positive photoresist was spin coated onto the metal layers and patterned using photolithography with another pre-designed MASK-II to remove excess Al thin film in the Zig-Zag region, Figure 4d.

Here, the Ti film deposited on glass substrate was used as a resistance layer to generate Joule heat, and as well as an adhesion layer to improve mechanical stability of the film micro-heater. What needs to be emphasized here is that, the Al film deposited on top of Ti film was used as a conductive layer to
reduce the resistance of the non-heated area, and improve the micro-heater operating efficiency. The fabricated thin film-resistor based micro-heater is shown in Figure 5. Obviously, the manufacturing process is relatively simple and could be completed using only two photolithography processes.

![Figure 4](image-url)  
**Figure 4.** Schematic drawing of fabrication process of Al/Ti micro heater on glass substrate.

### 3. Experimental result

Here, thin-film resistor the resistor before and after the removal of Al in Zig-Zag region, as shown in Figure 5. Typically, the thickness of Ti/Al is 200nm/70nm for Type-I micro-heater, and 600nm/70nm for Type-II micro-heater. Here, Ti layer acts as both the resistor and the adhesion layer, while the Al layer acts as both the conductor and contact pad.

![Figure 5](image-url)  
**Figure 5.** Photograph of the resistor before and after the removal of Al in Zig-Zag region.

In order to observe the transient Al/Ti micro-heater resistance, a custom circuitry was designed. Figure 1(b) schematically shows equivalent model of the micro-heater and the schematic diagram of the circuit prototype. Generally, the electrical properties of conventional metal body materials can be queried through relevant data sheets, but the differences between the properties of metal thin film materials and bulk materials cannot be easily replaced. Next, resistance of the micro-heater was performed in room temperature with multimeter. Here, the resistance of Al/Ti film resistor before and after the removal of the Al thin film in the Zig-Zag region, measured results are shown in Table 2. The resistances of the two types of heaters were tested by a multimeter, and results showed that resistance of the heaters can be effectively controlled by the thickness of the film.

| Resistance (Ω)       | Type-I   | Type-II  |
|---------------------|----------|----------|
| Before Remove Al    | 114±15   | 32±3     |
| After Remove Al     | 1430±114 | 233±28   |
Average temperature of the micro-heater can be determined indirectly by measuring the variation of heater resistance, and this has been validated as an accurate strategy for obtaining transient temperature [3]. As the temperature increasing was induced by Joule heat, consequently, an experimental calibration law between electrical resistance and temperature could be able to be extracted. We can find that during the room temperature to 100°C, good linear relationship can be easily obtained.

4. Conclusion
The thin film resistor has a simple structure and a feasible processing technology, and is particularly suitable as an effective micro-heater for Joule heating and suitable for integration with MEMS devices. Resistance of the heater can be designed by the thickness of the Ti film. Experimental results of this paper can be a good foundation for future research and application. This kind of micro-heater is especially useful for short temperature pulse applications.

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