Design and performance of NiCr-based micro-heater with lower excitation energy

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Abstract. Low energy and miniaturization are two main development directions for the MEMS (Micro-Electro-Mechanical System) -based initiator. The MEMS-based initiators or called fire components were fabricated by the way of that the secondary explosive charges were coated or synthetized with in-situ method onto the NiCr-based micro-heater surface. The firing voltage experiments of the fire component under capacity loading were performed. The fire voltages of the fire components with rectangle micro-heater increase linearly with the increasing of micro-heater’s width, and decrease with the increasing of micro-heater’s thickness. The fire voltages of the fire components with Pyrex7740 substrate cut down to 50%, compared to the fire component with silicon substrate. The fire component with lower explosive density contributes to reduce the fire voltage. The micro-heater with parallel connection structure or called parallel micro-heaters cannot have lower fire voltage than the single micro-heater, but have more reliability to initiate the secondary explosive.

1. Introduction

According to structural characteristics and material, micro-heater include elementary metals [1, 2] (such as Al, Ni, Cr, etc.), metal composites [3-5] (such as Al/Ni, Ni/Cr, Pt/W, etc.), energetic metal composites [6,7] (such as Al/CuO, Zr/CuO, Mg/CuO, Al/MoOx, etc.), semiconductor bridges [8, 9], and explosive foils. NiCr-based micro-heater is one of the most important micro-heaters, because it has very stable performance.

M. Birkett [10] prepared Ni-Cr and AlCu thin film resistors by magnetron sputtering. The effects of annealing on the electrical properties of the two thin film resistors were compared. Finally, AlCu was used in a lower resistance range. The optimized sputtering conditions and process for preparing AlCu thin film resistors were also obtained through experiments. MP Nguyen [4] used a magnetron sputtering method to prepare a 200-nm-thick Ni-Cr thin film resistor on a SiO2/Si substrate, and obtained the thin film structure morphology, resistance temperature coefficient and deposition temperature relationship. Bao Bingliang [11] designed a new optical fiber sensor to measure the temperature of micro-sized metal film bridge under constant current excitations, by the Fabry–Perot interferometric technology for high temperature measurements and quick temperature response. At
present, there have been a lot of researches on the manufacturing process and structural characteristics of NiCr-based micro-heater, while the relationships between the structure and the performances were not focused on.

This article focus on the relationships between the structure and the performances. Based on the research on the design and fabrication of micro-heater and the testing of characteristic parameters, this paper uses theoretical analysis, numerical calculations and experiments. The combined method establishes the structure-activity relationship of the micro-heaters, obtains relationship between the micro-heaters and the lower-level charge, and provides technical support for the low-energy and miniaturized structure design of the micro-heaters.

2. Design and fabrication of NiCr-based micro-heater

2.1. Structure design
Two types of NiCr-based micro-heater were designed. One of the micro-heater is rectangle structure, and the other is parallel connection structure, both of structures were illustrated in Figure 1. The size of rectangle micro-heater includes length and width, and the micro-heater with parallel connection structure were combined by four rectangle micro-heaters by the way of parallel connection. Three kinds of parallel micro-heaters are design:

(A) The size of the four rectangular micro-heaters are all 160μm×160μm, and this kind of micro-heater is named sample1;

(B) The size of the four rectangular micro-heaters are all 160μm×80μm, and this kind of micro-heater is named sample2;

(C) The dimensions of the four rectangular micro-heaters are 160μm×160μm, 160μm×160μm, 160μm×80μm, and 160μm×80μm, respectively, and this kind of micro-heater is named sample3.

Figure 1. Design of NiCr-based micro-heater.

2.2. Fabrication procedure
The fabrication process of the NiCr micro-heater is: cleaning → magnetron sputtering NiCr →
homogenization → exposure → etching NiCr → Magnetron sputtered conductive layer (usually Cu) → exposure → etching Cu → cleaning → sample, and the specific procedures is shown in figure 2.

Figure 2. Fabrication procedure of NiCr-based micro-heater.

A profilometer was used to test the thickness of the NiCr micro-heater. Four kinds of film thicknesses were designed. The design thickness and actual thickness are shown in table 1. The thickness of the Cu pad is 2.83μm. There is an error of not more than 7% between the design thickness and the actual thickness.

Table 1. Thickness of the NiCr-based micro-heater.

| design thickness (μm) | 0.70 | 0.90 | 1.10 | 1.30 |
|-----------------------|------|------|------|------|
| actual thickness (μm) | 0.72 | 0.96 | 1.17 | 6.37 |
| error(%)              | 2.86 | 6.67 | 15.45| 2.37 |

3. Performance of rectangle NiCr-based micro-heater

The surface of the completed micro-heater is coated with lead styphnate charge to form an energetic component. According to the Langley method, a firing experiment is performed under the condition of 94μF capacitor excitation to obtain the firing voltage.

3.1. Parameters of micro-heater effect on the performance

The effect of the width of the NiCr micro-heater on the firing sensitivity of energetic components is studied. The results are shown in figure 3. The thickness of the micro-heater is 0.9μm, 1.1μm, and 1.3μm, respectively, and the length is 160μm.
Figure 3. Relationship between firing voltage and micro-heater width.

The results in figure 3 show that, on the whole, the firing voltage of an energetic component increases approximately linearly with the increase of the width of the micro-heater.

Rectangular NiCr micro-heater with thicknesses of 0.7μm, 0.9μm, 1.1μm, and 1.3μm were designed, and the influence of the thickness of the micro-heater on the firing voltage of energetic components was obtained, as shown in figure 4.

Figure 4. Relationship between firing voltage and micro-heater thickness.

The results in figure 4 show that, in general, as the thickness of the micro-heater increases, the average firing voltage and 99.9% response firing voltage of the energetic components continue to decrease.

Rectangular NiCr micro-heater with lengths of 120μm, 160μm, 200μm, and 240μm, thicknesses of 0.9μm and 1.1μm, and widths of 160μm were designed. The influence of the length of the micro-heater on the firing voltage of energetic components was obtained, as shown in figure 5.
According to the results in figure 5, a comprehensive comparison shows that when the size of the NiCr micro-heater is $120\mu m \times 160\mu m \times 0.9\mu m$, the average firing voltage and 99.9% firing voltage of the energetic component are the lowest, which are 5.08 V and 6.97 V, respectively. The average firing voltage and 99.9% firing voltage were the highest at $160\mu m \times 0.9\mu m$, which were 8.75V and 36.1V, respectively. On the other hand, on the whole, there is no obvious change between the average firing voltage and 99.9% response firing voltage of the energetic components and the length of the micro-heater.

The Langley method was used to test the firing voltage of energetic components with different resistance values of the micro-heater. The average firing voltage, 99.9% firing voltage, and 0.1% firing voltage of the energetic components were obtained. The results are shown in figure 6.

It can be seen from figure 6 that when the micro-heater has different resistance values, the firing voltage of the energetic component does not change significantly, that is, the resistance value of the micro-heater does not significantly affect the ignition performance of the energetic component.

The selection of the substrate material is compatible with the MEMS pyrotechnics serial structure and manufacturing process. Secondly, it is necessary to consider the physical performance parameters of the substrate material's thermal conductivity and resistivity. Pyrex7740 glass and silicon were selected as the substrates of the micro-heater in the energetic components, and the firing performance
test was performed. The results are shown in Table 2.

**Table 2.** Test results of firing voltage of energetic components with different substrates.

| substrate    | sample counts | capacity/μF | 50% firing voltage/V |
|--------------|---------------|-------------|----------------------|
| Pyrex7740    | 15            | 33          | 5.28                 |
| silicon      | 15            | 33          | 11                   |

From the results in Table 10, it can be seen that when the substrate material is Pyrex7740 glass, the average firing voltage of the energetic component is reduced by 50% compared to the average firing voltage of the energetic component using a silicon substrate. According to relevant research results, the lower the thermal conductivity, the worse the thermal conductivity, the smaller the heat loss, and the faster and faster the heat accumulation of the micro-heater. The higher the temperature of the micro-heater, the higher the temperature passed to the next charge, the more favorable it is to form a hot spot. This is why the micro energetic component of Pyrex7740 glass with low thermal conductivity has a lower firing voltage.

### 3.2. Parameters of the explosive effect on the performance

The NiCr micro-heater is bonded to the explosive cavity, and a copper azide secondary explosive is generated in situ in the explosive cavity to form an energetic component to carry out firing test.

When the thickness of the secondary explosive is 0.5mm, the initiation of the explosive is studied in the range of the diameter of the explosive from 0.2mm to 1.0mm. The results are shown in Table 3.

**Table 3.** Firing voltage of energetic components under different explosive diameters

| No. | diameter/mm | thickness/mm | mass/mg | initiated |
|-----|-------------|--------------|---------|-----------|
| 1   | 1.4         | 0.5          | 1.4mg   | yes       |
| 2   | 1.2         | 0.5          | 1.2mg   | yes       |
| 3   | 1           | 0.5          | 1.1mg   | yes       |
| 4   | 0.8         | 0.5          | 0.9mg   | yes       |
| 5   | 0.6         | 0.5          | 0.4mg   | yes       |
| 6   | 0.4         | 0.5          | 0.2mg   | no        |

The output performance of energetic components was tested. The explosive diameter was greater than 1mm, and the CL-20 explosive could be reliably detonated under certain voltage conditions. When the explosive diameter is 0.6mm ~ 1mm, higher voltage is required to detonate CL-20. When the explosive diameter is less than 0.6mm, CL-20 explosives cannot be detonated.

The design explosive density of energetic components are 0.6g/cm³, 1.2g/cm³, and 2.34g/cm³, respectively, and the micro-heater is NiCr. The average firing voltage of energetic components at different densities is shown in Figure 7.
Figure 7. Average firing voltage of micro energetic devices at different densities

When the explosive densities of energetic components are 0.6 g/cm$^3$, 1.2 g/cm$^3$ and 2.34 g/cm$^3$, the average firing voltages of energetic components are 7.78 V, 6.04 V and 6.40 V, respectively. This also shows to a certain extent that a larger explosive density is beneficial to reduce the firing voltage of energetic components.

4. Performance of parallel structural NiCr-based micro-heater
Considering the substrate material, the shape and size of the micro-heater structure, the firing energy of the micro-heater of the conventional design structure is close to the limit. In order to further reduce the firing voltage or firing energy of the micro-heater, a new structure design or a new type of principle design. In order to further reduce the firing voltage of micro-heaters, the parallel structure design and performance test of the micro-heaters were carried out.

The surface of the completed parallel micro-structured micro-heater was coated with lead styphnate charge to form an energetic component. The firing voltage of four parallel micro-structured micro-heater was tested by Langley method. The results are shown in table 4. The firing capacitor is 94 $\mu$F.

| No. | sample | 50% firing voltage/V | 99.9% firing voltage/V | 0.1% firing voltage |
|-----|--------|-----------------------|------------------------|--------------------|
| 1   | pc-1   | 4.20                  | 9.25                   | -0.8               |
| 2   | pc-2   | 5.60                  | 10.79                  | 0.4                |
| 3   | pc-3   | 4.00                  | 11.65                  | -3.6               |
| 4   | pc-4   | 4.68                  | 11.60                  | -2.28              |

It can be seen from table 4 that compared with the firing voltage of a single micro-heater in a parallel micro-heater, the firing voltage of a parallel micro-heater does not decrease or increase significantly.

5. Conclusion
The MEMS-based initiators or called fire components were fabricated by the way of that the secondary explosive charges were coated or synthetized with in-situ method onto the NiCr-based micro-heater surface. The firing voltage experiments of the fire component under capacity loading
were performed. The fire voltages of the fire components with rectangle micro-heater increase linearly with the increasing of micro-heater’s width, and decrease with the increasing of micro-heater’s thickness. The fire voltages of the fire components with Pyrex7740 substrate cut down to 50%, compared to the fire component with silicon substrate. The fire component with lower explosive density contributes to reduce the fire voltage. The micro-heater with parallel connection structure or called parallel micro-heaters cannot have lower fire voltage than the single micro-heater, but have more reliability to initiate the secondary explosive.

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