Electro-thermal analysis of MEMS microhotplates for the optimization of temperature uniformity

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Abstract

This paper presents a microhotplate working up to 1200°C with improved temperature uniformity by optimizing the geometry of the thin-film resistor. By varying the linewidth of meandering resistive tracks, heat is generated in such a way to have more homogeneous temperature distribution. The microhotplates are fabricated using molybdenum as conductive material for the heater. Infrared thermal mapping shows that the temperature variation over the heated area is reduced from an initial 13% to 4%.

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1. Main text

The use of MEMS microhotplates is rapidly increasing for gas sensors, thermal actuators, infrared emitters [1] and recently for in-situ microscopy [2]. Devices for such applications require low power consumption, robustness, and stability. Moreover, temperature uniformity over the heated area is often a crucial specification. Fig.1a shows the schematic of a common MEMS microhotplate consisting of a thin-film heater wire embedded in a free-standing membrane. When electrical power is applied, heat is generated by Joule effect along the conductive path. Typically, meander-shaped resistors produce an uneven thermal profile with a hot spot in the central region, mainly due to high thermal resistivity of the thin supporting membrane. Several solutions have been proposed [3,4,5]. In this paper an improvement of thermal uniformity is achieved by using a single thin-film metal layer and varying the linewidth along the meander-shaped heater. In this way less heat is generated towards the center, thus improving the thermal profile over the sensitive area. The design of the microhotplate is based on finite-element analysis. The
microhotplate is fabricated by using sputtered molybdenum as conductive material, embedded in a membrane of LPCVD SiN [6]. It is characterized by infrared thermal imaging.

2. Fabrication

The microhotplate (Fig. 1a) is fabricated according to the process flow described in [6]. It consists of a 200 nm thick molybdenum resistor patterned as a four contact pads spiral with 300x300 μm² footprint. It is covered with 300 nm PECVD oxide to prevent oxidation of the molybdenum during processing. Finally, it is sandwiched between two 500 nm LPCVD SiN layers. The 1x1 mm² free standing membrane is released by anisotropic wet etching.

3. Finite-element analysis

Finite-element simulations were used to design the optimum geometry. In order to have an accurate prediction of the behavior of the real structure, it was important to determine the most relevant parameters such as the convective heat transfer coefficient and the thermal conductivity.

The convective heat transfer coefficient plays a fundamental role in the thermal behavior of the device. Usually, it is slightly dependent on temperature. It was extracted for our geometry by a combination of lumped element modeling [7] and measurements done on a reference microhotplate [6]. The reference, named here G1, consists of a spiral with a constant linewidth of 18 μm and spacing between the lines of 12 μm. The temperature coefficient of resistance (TCR) of the molybdenum is 2.45 ppmK⁻¹, which is constant up to 700°C.

The heat loss by convection to air can be represented as [7]:

\[ P_{\text{conv}} = \frac{\Delta T}{2hA} \]  

(1)

where the factor 2 takes into account the heat exchange from both sides of the membrane, \( \Delta T \) is the temperature difference with respect to the ambient, \( A \) is the heater footprint and \( h \) is the convective heat transfer coefficient. Therefore, \( h \) can be determined by measuring the power consumption due to convection on the real device. The power consumption \( P_{\text{conv}} \) was measured as a function of the operating temperature, in air and in vacuum (Fig.2). By knowing \( P_{\text{conv}} \), the coefficient \( h \) was calculated using (1).

Fig. 1 (a). Schematic cross section of the microhotplate, as well as the possible paths of heat flow. The heater of 200 nm Mo (orange) is sandwiched between two 500 nm layers of LPCVD SiN (green) and 300 nm PECVD SiO₂. (b) Layout of the new geometry G2, with improved temperature uniformity.
As can be seen in Fig.3, $h$ is indeed dependent on the temperature and the use of a constant value would bring to misleading results. This model was added to the COMSOL library.

Measurement in vacuum showed a nearly linear dependence of the power consumption from the temperature. Therefore, the thermal conductivities of the membrane and the molybdenum were assumed constant (1.35 and 84 WmK$^{-1}$, respectively). Simulations are in agreement with experiments (Fig.3).

Electro-thermal analysis on the geometry G1 (Fig.4) shows that a temperature gradient is present with a variation of about 15% from the middle to the edge of the heated area. The new geometry G2 (Fig. 1b) has a linewidth which increases from 14 $\mu$m to 24 $\mu$m towards the middle area in order to generate less heat. Simulations (Fig.4) show that the temperature distribution in G2 is much more homogenous and the variation is about 4%, as can be seen in the 1D profile (Fig.5) extracted from the thermal maps of Fig. 4.

4. Experimental results

The microhotplates were diced in 3x3 mm$^2$ chips and mounted on TO5 packages for the infrared thermal mapping. The imaging of the temperature distribution was done in dedicated measurement setup [8] using Merlin MID IR camera at atmospheric pressure. The spatial resolution is 2.5 $\mu$m and the temperature range 20-350°C with a thermal resolution of 1°C. The thermal maps of the geometries G1 and G2 are shown in Fig 6. G1 clearly exhibits a hot spot in the middle of the metal coil with 13% gradient from the center to the periphery. On the other hand, the geometry G2 shows a uniform temperature distribution with about 4% variation over the heated region.
Thermal imaging is in good agreement with finite-element simulations (Fig. 4) thus proving how crucial it is to determine the proper model for the convective heat transfer coefficient. A further evidence of the improved thermal behavior of G2 at higher temperature was given by the optical images of the microhotplate when brought to glowing at 900°C (Fig. 7). The geometry G1 becomes incandescent in the center while no significant hotspots are observed in G2. Failure occurs above 1200°C [6].

Conclusions

A new meander-shaped microhotplate using molybdenum as conductive material was presented. The new geometry, larger linewidth at the center, smaller at the edges of the hot plate, resulted in a temperature variation over the heated area below 4%. Moreover, no hot spots are visible up to 900°C.

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