Sensors and Actuators A 257 (2017) 58–64

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A novel polyimide based micro heater with high temperature uniformity

Shifeng Yu[a], Shuyu Wang[b], Ming Lu[c], Lei Zuo[a,*]

[a] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA, 24061, USA
[b] Department of Mechanical Engineering, Stony Brook University, Stony Brook, NY 11794, USA
[c] Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, NY 11973, USA

ARTICLE INFO

Article history:
Received 29 June 2016
Received in revised form
19 September 2016
Accepted 5 February 2017
Available online 6 February 2017

Keywords:
Micro heater
Bio-calorimetry
Temperature uniformity
Polyimide membrane
Fast response

ABSTRACT

MEMS based micro heaters are a key component in micro bio-calorimetry, nondispersive infrared gas sensors, semiconductor gas sensors and microfluidic actuators. A micro heater with a uniform temperature distribution in the heating area and short response time is desirable in ultrasensitive temperature-dependent measurements. In this paper we propose a novel micro heater design to reach a uniform temperature in a large heating area by optimizing the heating power density distribution in the heating area. A polyimide membrane is utilized as the substrate to reduce the thermal mass and heat loss which allows for fast thermal response as well as a simplified fabrication process. A gold and titanium heating element is fabricated on the flexible polyimide substrate using the standard MEMS technique. The temperature distribution in the heating area for a certain power input is measured by an IR camera, and is consistent with FEA simulation results. This design can achieve fast response and uniform temperature distribution, which is quite suitable for the programmable heating such as impulse and step driving.

1. Introduction

Micro heaters consists of a heating element and substrate, and have been applied widely for temperature control in MEMS sensors, especially in bio-calorimeters [1], gas sensors [2], microfluidic actuators [3] and IR applications [4]. There has a lot of work investigating different materials used as the heating source such as polysilicon [5], SiC [6], TiN [7], Pt [8], and Au [9]. When a voltage is applied to the terminals of the heater, which is often made of resistor materials, it will generate a certain amount of Joule heat. A thin film insulator such as SiO_2, Si_3N_4 or polymer membrane is usually used as the substrate for the heater. To reach high thermal insulation, the thin film substrate is usually suspended using several beams for support. Since MEMS fabrication is usually carried out on silicon wafers, which require a lot of etching work, it is time consuming and costly [10]. Thin films like SiO_2 and Si_3N_4 can only sustain small loads due to their poor mechanical strength, so the application of the heater based on these substrates is limited to some gas sensors and IR devices [11–13]. Recently however, polymer membranes, especially polyimide, have gained a lot of attention [14,15] due to their robustness, low thermal conductivity, and simple fabrication process. In addition, the thermal expansion coefficient of polyimide membrane is quite close to that of a silicon wafer, which makes it quite comparable with the IC fabrication process. In fact, some companies such as Minco and Omega already have similar products by employing a meandering resistive track on polyimide to form a heating element.

Compared to the traditional hotplate, a MEMS based micro heater needs much lower driven power/voltage and costs much less. Due to the small size and simple structure, a micro heater is much faster in various types of thermal response. Recently, many papers reported their work in developing novel MEMS heaters which can achieve high heating temperatures and short response times [4,5,7], however, while most of them mention the temperature distribution in the heating area, only a few works report about how to improve the temperature uniformity [16]. Good heating uniformity can increase the selectivity and sensitivity of the device which is potentially important in ultrasensitive NDIR gas sensing and micro calorimetry. For an NDIR gas sensor, the emissivity is both temperature and wavelength sensitive [17] while calorimetry measurements are directly temperature related [18]. Previous research results show that uniform heating power density will lead to non-uniform temperature distribution [19]. By thorough analysis of the heat transfer on the surface of the heater and carefully distributing the heating power, the heating area can reach high temperature uniformity.

---

* Corresponding author.
E-mail address: leizuo@vt.edu (L. Zuo).

http://dx.doi.org/10.1016/j.sna.2017.02.006
0924-4247/

Table 1
Parameters for the polyimide based heater under different heating power distribution.

k (W/mK)	t (m)	h (W/m^{2}K)	r (m)	Heating power distribution (1) σ_1 (W/m^2)	Heating power distribution (2) σ_2 (W/m^2)	Heating power distribution (3) σ_3 (W/m^2)
0.12	7×10^{-6}	7.8	0–0.001	1000	$1.76 \times 10^5\ (0.005 + r)$	$3.75 \times 10^5\ (0.002 + r)$
			0.001–0.02	0	0	0

In this paper we propose a novel micro heater on a polyimide membrane with high temperature uniformity and short thermal response time. A novel process is introduced to fabricate the flexible substrate using liquid polyimide. A gold resistor is utilized to release Joule heat. For the heater design, a numerical method is developed to analyze the relationship between the heating power distribution and the temperature uniformity. The optimization of temperature uniformity in the heating area is completed using an ANSYS thermal MEMS simulation. A prototype is then fabricated based on the simulation and tested. The measurement and simulation results are consistent. The time constant for the step response is also measured when 2 µL water droplet is loaded on the substrate.

2. Design and fabrication

2.1. Temperature distribution

The micro heater is composed of a resistive Au/Ti trace on a polyimide membrane. When a certain amount of heating power is applied to the heater, the temperature is quickly redistributed over the suspended polyimide membrane. The response time is on the milli-second scale due to the small thermal mass of the suspended polyimide membrane. The heat will ultimately be transferred through conduction to the periphery and convection with the air will occur along with some thermal radiation. When temperature in the heating area is less than 500 K, the heat loss through radiation can be neglected compared to the total heating power supply [20]. Due to the low thermal conductivity of the polyimide membrane, the temperature attenuates rapidly in the non-heating area. When stable, most of the heat will be transferred to the air from the heating area through heat convection directly. Natural heat convection is caused by buoyancy forces due to the density difference caused by temperature variations in the air. When the sample area is heated, the fluid near the boundary is warmed, and becomes lighter. The buoyancy causes the fluid to rise and be replaced by a cooler fluid that will in turn be heated continuing the process [21]. When the polyimide based micro heater is placed horizontally, the coefficient of heat convection for the upper surface is different from that for the lower surface. The coefficient of heat convection depends on the gas which serves as the cooling fluid, the surface temperature of the sample and the geometrical configuration of the heater. The temperature distribution in the heating area is greatly affected by the contour of the heater and the distribution of the heating trace. The temperature distribution can be expressed by the Poisson equation [22] as follows [24]:

$$-\nabla(kt \cdot \nabla T) = \sigma + h(T_{air} - T) \tag{1}$$

$$h = \frac{0.54kR_{aL}^{0.25}}{L} + \frac{0.27kR_{aL}^{0.25}}{L} = \frac{0.81kR_{aL}^{0.25}}{L} \tag{2}$$

$$\sigma = \frac{dP}{dS} \tag{3}$$

where: k is the thermal conductivity, and t is the thickness of the membrane, σ is the heating power density in the heating area, h is the total coefficient of heat convection for the upward and downward surfaces, L is the characteristic length of the heater, specified by the area over the perimeter, T_{air} is the temperature of the air which is assumed constant, and T is the local temperature in the membrane. Since the heater consists of a series of concentric gold traces, and the polyimide membrane is much larger than the heater itself, the temperature distribution in the plane of the membrane is isotropic, so a polar coordinate system is used to express Eq. (1):

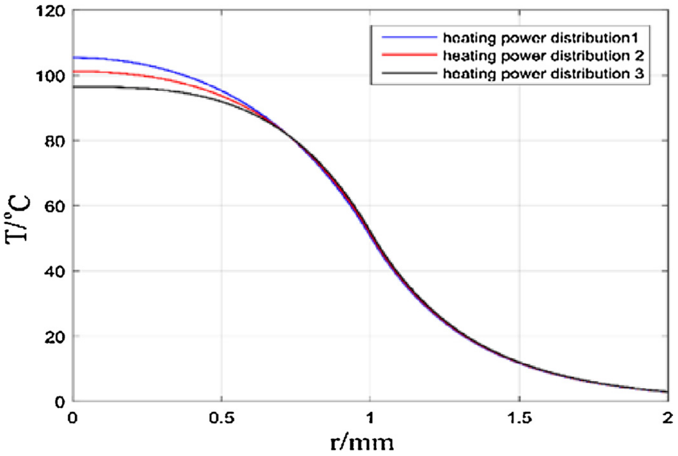

Fig. 1. Temperature distribution in the membrane related to different power distribution.

$$\frac{kt}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \sigma + h(T_{air} - T) = 0 \tag{4}$$

For the horizontally placed micro heater, h is around 7.8 W/m^{2}K [23]. Based on Eq. (4), a numeric method is carried out to calculate the temperature distribution for the given normalized heating power density distribution.

In the Matlab numerical simulation, the polyimide substrate is a round plane with the radius of 2 cm. The heating area is located in the center with a radius of 1 mm, with a total heating power of 9.42 mW. In the center of the heating area (r = 0), the temperature reaches maximum or minimum while at the edge of the membrane, the temperature is set to T$_{air}$ since the temperature attenuates rapidly in the non-heating area. For the calculation, we assume a different heating power distribution in the heating area shown in Table 1. As with the previous result, uniform heating power density will generate a non-uniform temperature distribution [17]. To increase the uniformity of the temperature in the heating area, a different spline function is used to represent the power density for the calculation. Basically, the heating power should gradually increase from the center to the edge of the heating area. Fig. 1 shows the preliminary result of how the heating power distribution affects the temperature distribution. In distribution 1, the heating area has a uniform heating power density 1000 W/m^2, The numerical result shows T is 104 °C at the center of the heater, and reduces to 50 °C at 1 mm from the center. In distributions (2) and (3), the heating power density linearly increases with r in the scale 0–1 mm. In distribution (2), heating power density goes from 880 W/m^2 at the center to 1050 W/m^2 at 1 mm. While in distribution 3, the heating power density at the center is 750 W/m^2 and 1125 W/m^{2}at 1 mm. From 1–3, the temperature uniformity in the heating area is improved, but still not so promising (Table 2).