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The critical impact of temperature gradients on Pt filament failure

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ABSTRACT

This work established the correlation between the location of temperature gradients and the positions where breakdown is observed on different Pt filament layouts in cantilever and full membrane type micro-hotplates. Focusing on practical aspects like in real operation, self-heating was applied to investigate the limitations of high temperature application and to reveal the fatal failure mechanisms. Besides electromigration, another phenomenon playing dominant role in the breakdown of the filaments, the temperature gradient driven thermomigration of Pt was identified. This limits the local allowable temperature gradient to <0.4 °C/μm for operation temperature above 700 °C.

1. Introduction

Low power dissipation MEMS devices often require stable integrated heaters to provide locally elevated temperature for sensing, refreshing of active surfaces, or actuating mechanical components. Most frequently micro-hotplates are used in gas sensing applications of different transduction principles. Conductivity type sensors measure the chemisorption driven resistance change of semiconducting metal oxides [1,2], FET structures [3], and calorimetric devices detect the heat conductivity of the ambient or the exothermal heat generated by catalytic combustion [4,5]. Flow and pressure sensors making use of local heating are also prominent applications [6,7]. Although most of these applications need moderate operation temperatures up to 300–400 °C, some of the catalytic processes are effective well above 500 °C only [8]. The ideal micro-hotplate has to meet three substantial requirements: low power dissipation to facilitate portable device operation, homogeneous temperature distribution for designed performance, and most importantly, stable operation during the years-long lifetime of devices.

To minimize power consumption, thin membranes of various geometries are formed with integrated heaters. Full membranes or perforated designs with heaters suspended by four or two arms, as well as of cantilever-type are commonly used to further limit heat loss by conduction [9–14].

Due to the high thermal load the thin film materials of the hotplate must be selected such as to minimize the thermomechanical stress. The most frequently used material combinations to form mechanically stable membranes are low residual stress SiN_x [10,15] layers as well as combination of compressive SiO_2 and tensile Si_3N_4 in a multilayer structure [4,5,16–18]. In general, reduction of mechanical stress below 150 MPa can eliminate the stress induced breakage of the membrane [19,20].

The reliability of the filament remains, however, a crucial issue, especially when high temperature operation is targeted. Beside the essential stability of the electrical and structural properties, for controlling the temperature of the hotplate a definite relationship between heater resistance and temperature (thermal coefficient of resistance: TCR) has to be stabilised. Due to its high temperature coefficient of resistivity over a wide temperature range, the most frequently applied heater material is platinum [6,9,10,11,21]. For limited temperature applications MOSFET heaters [18] were also investigated. The CMOS compatible polysilicon has also been proposed as heater material [4], but the indefinite TCR, and the changing polycrystalline structure above 600 °C restrict the use of poly-Si heaters to the temperature range between 300 and 500 °C [22,23]. Suspended single crystalline Si filaments by porous Si micromachining were also early proposed, but in that case device lifetime was restricted by the silicide formation in the hot contact regions [24]. The availability of SOI substrates made the single crystal-Si alternative attractive again, however, in view of long-term stability, the oxidation of Si at high temperature still remains a challenge [15,25].

The preferred filament is thus formed from thin film Pt because of its chemical inertness and high TCR. For adhesion improvement of Pt on Si and SiO_2 several materials were proposed, such as Ti, Ta, Hf [26–28].The best candidates, however, are said to be Al_2O_3 [29] and TiO_2 [30–32], because they form no intermetallic phases and the Pt integrity is also better preserved. Nevertheless, electromigration induced deterioration

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during device operation cannot be avoided. Based on accelerated lifetime tests most of the authors stated that the electro migration induced mechanical fracture is to blame for the final breakdown of the filament, and mechanical stress can accelerate the electromigration effect [33–35]. Courbat et al. in [36] hinted to the importance of temperature gradients which according to them, however, needs to be further investigated.

In the present work we particularly analyse the performance and degradation of a micro-hotplate structure with embedded TiO_2/Pt/TiO_2 filament at high temperature operation. We pointed out the crucial role of temperature gradient built up along the filament. The findings were justified for the most common filament layouts in the literature: meander and double spiral [8,14,15,19,21,33,37,38,39].

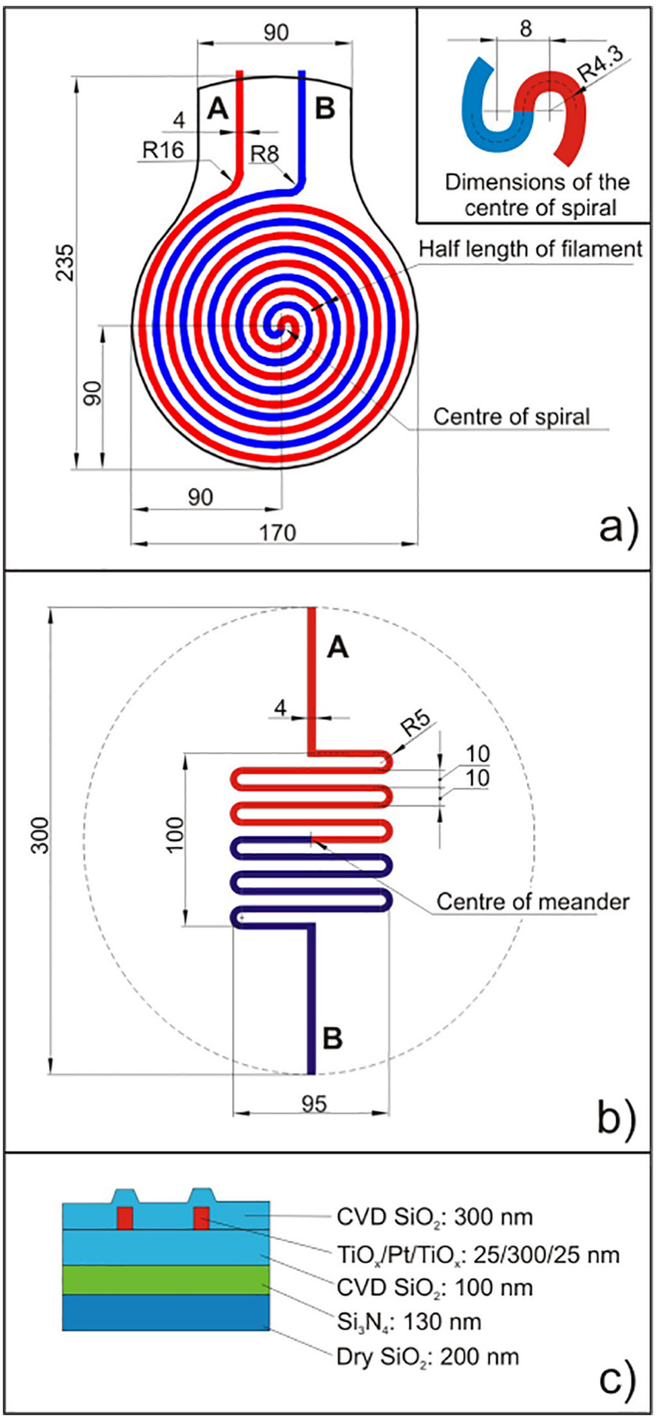

Fig. 1. Layout of the double spiral a) and the meander type b) hotplates investigated in this work. All dimensions and radii of curvature are given in μm. A and B denote the A and B arms of the spiral or A and B half of the meander. Schematics of the multilayer structure of the membranes are shown in c). Heaters with the given dimensions were used in every experiment.

2. Experimental

2.1. Design of micro-heaters

Full membrane and cantilever type hotplates with identical double-spiral heaters were manufactured and tested. In order to verify the results described in this work an alternative, meander type filament embedded in the same multilayer structure was also fabricated. The dimensions of the micro-hotplates are presented by Fig. 1a, b. Diameter of the full membrane was 300 μm.

Filaments are completely sandwiched between SiO_2 layers and the encapsulated Pt is not directly exposed to air during testing.

The multilayer structure to minimize the thermo-mechanical stress was elaborated earlier [17]. The 300 nm thick Pt filament is wrapped between two 25 nm thick TiO_2 layers to enhance adhesion to the SiO_2 layers beneath and atop, respectively (Fig. 1c). TiO_2 is known to prevent the formation of the Pt_3Ti intermetallic phase, and thereby offering an improved structural stability compared to metal adhesion layers for example Ti or Ta [30]. For membrane release in the cantilever-type structure a front side SiO_2-Si_3N_4 etching and back side DRIE were applied. The full membrane version in is processed similarly, but without front side etching.

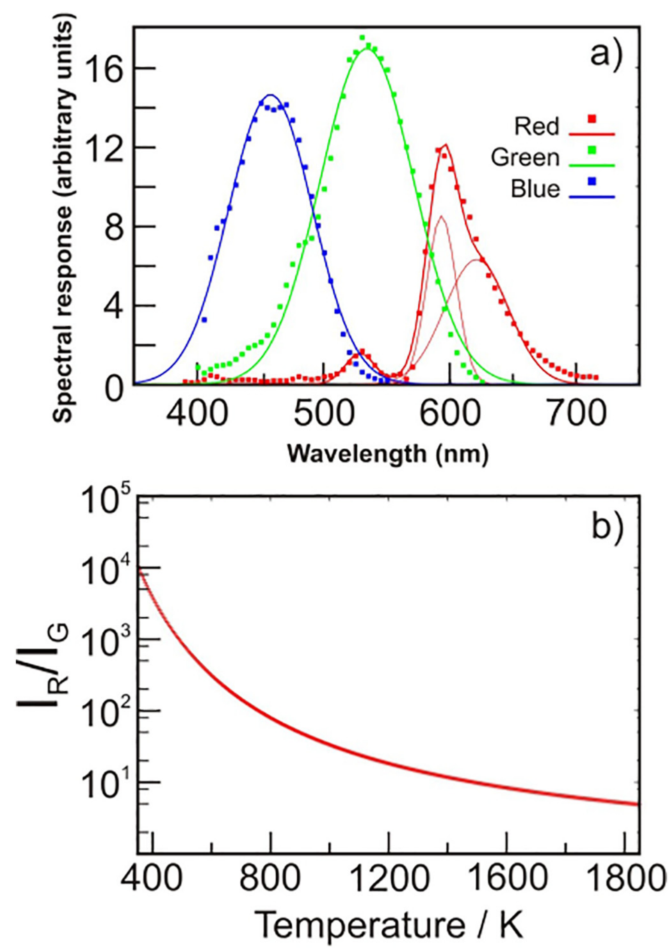

Fig. 2. a) Fitting the spectral response by Gaussian functions to determine the I_R, I_G, I_B intensity between 300 and 2100 K. b) Intensity ratio of the red and green channels (I_R/I_G) of the CCD spectral response.