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Design and analysis of integrated flow sensors by means of a two-dimensional finite element model

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Abstract

A model capable of providing quantitative predictions about the response of integrated thermal flow sensors is presented. The proposed approach exploits the versatility of the FEMLAB™ environment to introduce elements of a 3D description into a more computationally efficient 2D model. The simulations described in this work were aimed to check the consistence of the model with measurements performed on a real sensor and evaluate the actual benefits of changing some geometrical parameters with respect to the original configuration.

Keywords: Flow sensor; Integrated sensors; Finite element simulations

1. Introduction

In last years, many important microelectronic companies have been devoting a significant part of their research activity to the development of commercial products based on micro-electro-mechanical systems (MEMS). This process urged the development of CAD tools for MEMS design with characteristics of efficiency and reliability typical of the microelectronic design automation tools. However, the continuum nature of the structures, together with the general requirement of three-dimensional schematization, poses serious problems in terms of convergence of the numerical procedures and difficulty of physical description. With the increased power of today's computers and the improvement of the algorithms used, mechanical, thermal and electrostatic problems involving solid configurations result to be treatable. An exception is represented by integrated thermal flow sensors, a class of miniaturized devices with an impressive number of potential applications, often claimed in the related literature, but not demonstrated yet by their actual market relevance. Amongst the causes of this incongruity there is the lack of a tool capable of providing quantitative prediction of the sensor characteristics. Reliable simulation programs are necessary to carry on all the changes required to meet the specifications during the design phase. Furthermore, prediction of the sensor response would provide preliminary data useful to design the electronic readout channels, which are generally integrated on the same chip or package as the sensor and have to be tailored to the features of the latter.

Analytical methods produce interesting information about general aspects of the physical phenomena involved [1], but provide quantitative data only when an one-dimensional schematization is applicable [2]. In principle, this limitation can be surmounted by using a numerical approach, typically the finite element method. In this case, the precision of the data produced is strictly related to how closely the sensor geometry is represented. In many cases, such as the example presented in this paper, a three-dimensional model would be strongly required. However, convergence problems tied to the complexity of the fluid dynamics equations allow practical use of three-dimensional simulations only for very regular flow channel geometry (absence of steps and cavities) [3–6], simplified sensor structure [4,7] and/or reduced simulated volume [8]. On the other hand, two-dimensional simulations present less convergence problems and, in principle, can be used to simulate more realistic and irregular flow channel profiles. Typically, 2D simulations are applied to cross-sections defined by one direction parallel to the flow channel length and the other perpendicular to the substrate surface. Application is limited to sensor struc-

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ture where gradients along the third axis (perpendicular to the simulated cross-section) can be considered negligible [9–11]. Unfortunately, the configuration of many integrated sensors of primary interest does not satisfy this condition. In particular, devices obtained by means of front side bulk micromachining [12–14], such that described in next section, are formed by suspending elements with dominant heat exchange paths that cannot be included in a single 2D cross-section. Neglecting part of these conductances would result in large overestimation of the temperature reached by the heater. It should be observed that front side bulk micromachining is maybe the simplest choice to integrate flow sensors together with electronic devices by post-processing of standard integrated circuits. To our knowledge simulation of this kind of devices, maintaining the complex step and cavity configuration encountered by the flow, has not yet been presented in the literature.

In this work we present a method to introduce very specific terms in a realistic, well manageable two-dimensional model, in order to take into account also the main heat exchange paths along the third dimension. The two-dimensional nature of the model allows representation of complex flow channel configurations with reduced convergence problems. The method has been used to develop a model of a real micrometric thermal sensor to be simulated by means of the FEMLAB™ finite element platform. The tests, described in Sections 3 and 4, were aimed to check the consistence of the simulated results with the response of the real sensor and to explore the possibility to change some geometrical parameters of the latter in order to improve its performances.

2. Two-dimensional model

The model has been expressly developed to predict the behavior of integrated flow sensors characterized by the same structure as that of Fig. 1, depicting the sensor used for the experiments of Ref. [15]. The device consists of a heater (polysilicon resistor) and two temperature sensors (thermopiles) suspended on dielectric membranes to provide thermal insulation from the substrate. The output signal is proportional to the temperature difference between the downstream and upstream thermopile. It is worth noting that this structure is representative of a wide class of integrated flow sensors, which differ from Fig. 1 only for the type of temperature sensor, the geometrical dimensions or the shape of the suspended membranes.

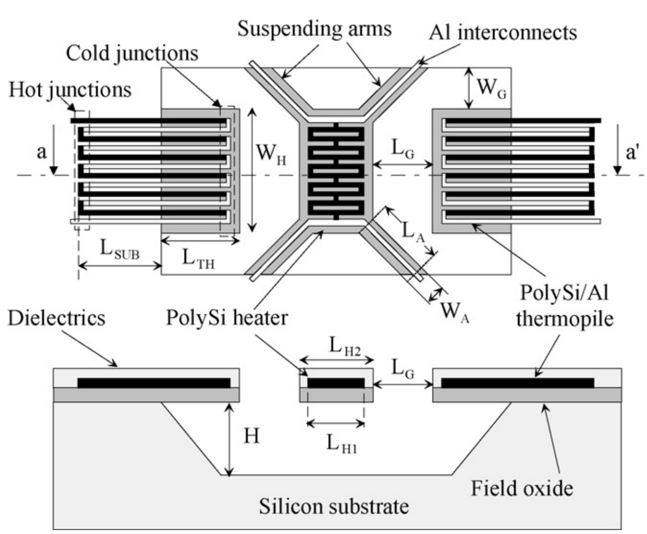

Fig. 1. Schematic top view (upper) and cross-section (lower) of the simulated flow meter (not to scale).

Table 1
Values of the sensors dimensions indicated in Fig. 1

L_G	61 µm
W_H	80 µm
W_A	25 µm
H	80 µm
L_{H1}	34 µm
W_G	34 µm
L_{TH}	30 µm
L_A	74 µm
L_{H2}	42 µm
L_{SUB}	80 µm

The simulations have been performed on a device model corresponding closely to the cross-section of Fig. 1 with main dimensions collected in Table 1.

In this work we have used the FEMLAB™ environment to find the temperature distribution in condition of forced convection regime for the two-dimensional arrangement shown in Fig. 2, where the sensor chip is placed inside a duct with a parabolic fluid velocity distribution imposed to one end. A temperature indicated with T_{sub} and equal to 298 K is applied to all the four walls (s_1–s_4) of the duct.

The sensing structure, placed at the distance d_{LE} from the chip leading edge is described according exactly to the cross-section of Fig. 1. In particular, the complex layer stacking present on the heater and thermopile has been respected as shown in Fig. 3(a).

In order to obtain an acceptable representation of the actual sensor behavior it is necessary to:

(i) properly set all the area quantities in the two-dimensional section corresponding to the correct volume quantities in the three-dimensional case;
(ii) introduce fictitious material characteristics that average the material properties encountered along the third dimension (*z*-axis);
(iii) introduce additional area quantities to represent major heat fluxes along the *z*-axis.

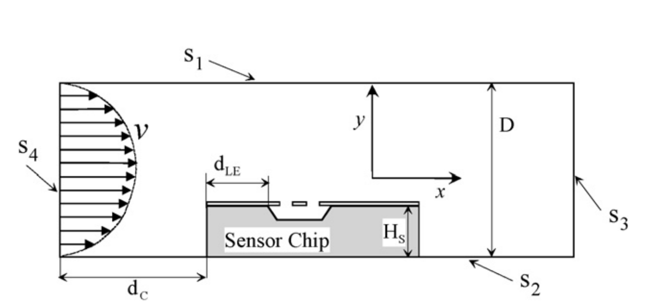

Fig. 2. Two-dimensional configuration used to represent the experimental case.