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Characterization of thermal conductivity in thin film multilayered membranes

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Abstract

In this paper we propose a novel approach for the thermal conductivity determination in thermal membrane-based devices. In the presented methodology, the fitting of experimental and simulated thermal dissipation of two resistive elements is used to characterize both the materials composing the membrane structure and the material used in the heating element patterning. The determination of this parameter, usually disregarded in most of the analysis, leads to a complete characterization of the structure and represents an improvement, as a better accuracy in the thermal properties of the membrane under study can be achieved. To demonstrate its effectiveness, the method has been applied to a already-fabricated flow sensor structure.

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Keywords: Thermal conductivity; Membranes; Micromechanical devices; Multilayers

1. Introduction

The power consumption of a thermal-effect based sensor depends on the fabrication materials as well as on a proper design. However, the optimisation of the sensor operation features at the design level requires the previous knowledge of the thermal properties of the materials that are going to be implemented in the structure. Due to their low thermal and electrical conductivity and its availability in standard microelectronic fabrication technologies, Si_3N_4 and SiO_2 have been widely used in micromachined structures [1–5]. Nevertheless, the variety of reported values of thermal conductivity of these materials when deposited as thin-film layers provides evidence of their dependence both on the type of deposition process—*Low Pressure Chemical Vapour Deposition* (LPCVD), *Plasma Enhanced Chemical Vapour Deposition* (PECVD), etc—and on their processing parameters [6] (temperature, gas concentration, pressure...). Values between 1.1 [7] and 1.4 W m^{-1} K^{-1} [8] have been reported for SiO_2 whereas values from 2.3 [9] to 25–30 W m^{-1} K^{-1} [8] can be found for Si_3N_4 in the literature. As a result, if the power consumption of a particular sensor structure is to be optimized at a design level, the strong dependence of thermal conductivity values on the fabrication process raises the need of characterizing the specific implemented layers.

In most of the reported studies about thermal conductivity in dielectric and metallic thin films, layers under study have been deposited on silicon substrates [10–12]. Nevertheless, in the *Microsystems (MEMS)* field, some authors have proposed the fabrication of micromachined test structures, so the thermal dissipation of a thermistor placed on these structures can be approached by means of analytical calculus. However, this method requires the on-purpose fabrication of high isolated structures such as cantilevers beams or suspended bridges with a very particular geometry [13–15]. Alternatively, the determination of physical properties in more complex structures that cannot be solved analytically can also be approached by means of mathematical simulations. Nowadays, a wide

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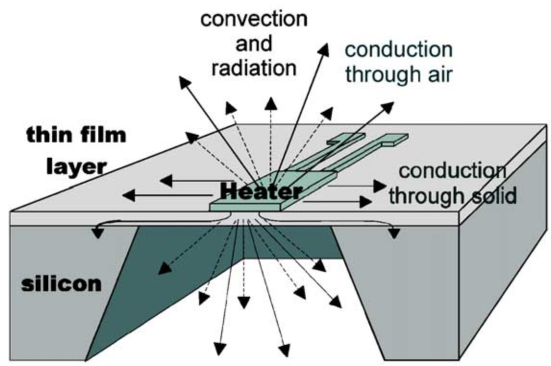

Fig. 1. Thermal dissipation mechanisms in a micromachined structure.

range of commercial simulation programs have arisen as a powerful design tool for the MEMS community. In this sense, the physical parameters of a theoretical model reproducing accurately the sensor working conditions can be tuned to fit the experimental thermal behaviour. Examples of this approach can be consulted in recent works, in which some authors have used simulation results from software based on *Finite Element* (FE) method of calculus to fit the temperature distribution in gas sensor membranes [16 17]. Generally, experimental data is obtained by scanning the sensor membrane with an *Atomic Force Microscope* (AFM) temperature probe or by recording the temperature distribution with an infrared camera.

In this paper, a new method of performing the comparison between experimental and simulation data for obtaining thermal conductivities in a set of sensor membranes is presented. The proposed method is based on the fitting of experimental and simulated thermal dissipation of a calorimetric flow sensor consisting of three resistive elements when working in vacuum conditions. As will be shown, this method not only takes benefit of already-fabricated structures but also simplifies the simulation model and increases the accuracy of the obtained results.

2. Experimental details

When supplying power to a heating resistor placed on a micromachined membrane, the heat generated by the Joule effect is dissipated through three different mechanisms: thermal conduction, convection and radiation. Fig. 1 illustrates the thermal dissipation mechanisms in a micromachined structure. In this way, heat is transferred, on one hand, along the membrane by means of thermal conduction through the solid materials and, on the other hand, to the surrounding air by means of conductive and convective mechanisms. In addition to this, when absolute temperatures are high enough, radiation losses turn to be an important mechanism of heat loss. In this study, temperatures are kept below 250 °C, so radiation phenomena can be disregarded without a significant change in thermal isolation. Moreover, as our sample is placed in a vacuum chamber, the effects of heat conduction and convection through air can be discarded. Thus, power dissipation occurs only by means of thermal conduction through the layers to be characterized, that is, the layers composing the micromachined membrane. The restriction of the simulation model to a solid structure decreases the number of unknown quantities. Moreover, the obtained solution from a FE simulation model is very sensitive to the properties of the modelled surrounding air and usually, the setting of realistic boundary conditions is a laborious task.

So in this work, the heat dissipation in vacuum of the membrane to be characterized has been measured and fitted to a FE model with the aim of determining the thermal conductivity of the membrane materials. The total heat flow Q through the sensor structure can be expressed as:

$$Q = G_S k_S (T_{hot} - T_{ref}) \tag{1}$$

where G_S accounts for geometrical factors, T_{hot} accounts for the temperature generated in the heating resistor, T_{ref} is the temperature of the silicon rim which usually corresponds to the room temperature, Q is the heat related to the power supplied to the heating resistor and k_S is the effective thermal conductivity of the structure. T_{hot} and T_{ref} are measured through the resistance value of the polarized resistor and a reference resistor placed on the silicon rim respectively. In this present case, k_S is the unknown parameter of the structure, and it depends of the thermal conductivity of the sensor membrane k_{mem} (that can be composed by a single layer or a multilayer) and the thermal conductivity of the heating resistor material k_{resis}, the contribution of which cannot be disregarded, as there will be also thermal losses along its connection tracks. It is clear that, when fitting the experimental dissipation of the central heating resistor with a FE model, the value of k_S will be determined, but it would not be possible to determine the

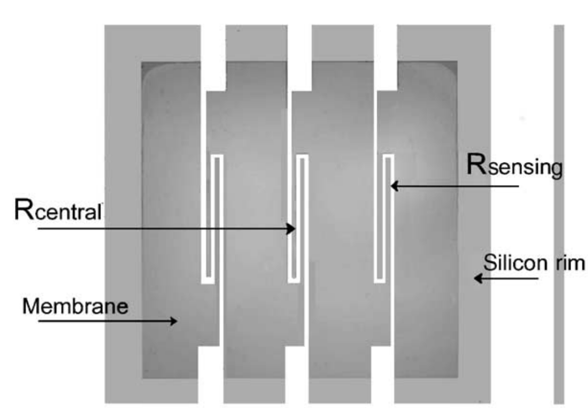

Fig. 2. Top-view photograph of one calorimetric flow sensor used in the measurements.