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3D Multiphysics Modelling of an SOI CMOS MEMS Thermal Wall Shear Stress Sensor

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Abstract

This work presents for the first time a 3-D model of an SOI CMOS MEMS thermal wall shear stress sensor using multiphysics approach. The model involves three different physical domains and, when compared with the experimental results, shows an excellent agreement in every condition.

After the validation process, the model has been used to perform a transient analysis on the device to evaluate the electro-thermal transient time, defined as the time required from the device to change its temperature from 10 to 90% of the steady state value when a step is applied to the biasing current.

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1. Introduction

MEMS technology is based on two technological steps: thin layer deposition of a wide range of materials and etching with different grades of selectivity and isotropy; this improves the devices performances compared to the traditional devices based on the same principle in terms of: thermal and mechanical inertia, spatial resolution, cut-off frequency and power needed to reach the same sensitivity [1].

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MEMS technology is extensively used in a wide range of sensing applications, with two possible approaches: direct when the quantity to measure is directly related to the signal output (often using moving elements) or indirect where a third physical quantity (temperature in the “thermal MEMS sensors”) is used to relate the two signals.

This paper analyses a thermal SOI MEMS CMOS sensor for the wall shear stress $\tau$, defined as the stress that a viscous fluid exerts on a surface because of the viscosity. The working principle for this device involves three coupled physical domain: joule heating, thermal conduction and forced convection (natural in still air).

While a number of thermal wall shear stress sensors has been reported in the literature [2,3], a few examples of numerical modelling, are either not 3-D [4] or missing the heat generation [5] whereas this work include a complete physical description in the real 3-D structure.

The device, the technology used to produce it and the working principle will be described in section 2. Later, in section 3, the numerical model is described in details, including all the approximations and assumptions done during the development process. Section 4 presents the numerical results, comparing them with the experimental ones. The data considered are: temperature profile in the structure and voltage outputs as function of $\tau$. Eventually, a transient simulation has been performed and the results presented in section 5.

2. Device

The device presented here is a thermal SOI MEMS CMOS flow sensor, the overall layout is shown in Fig. 1a and the process cross section (not to scale) in Fig. 1b.

A 2 $\mu$m×400 $\mu$m metal hot-wire, identified as R3, is located perpendicular to the flow direction and heated with a constant current of up to 10mA reaching a temperature of up to 300$^\circ$C. Four identical resistors (R1, R2, R4 and R5) are installed parallel to the heated element at a distance of 200 and 400 $\mu$m on both sides, using the metal Temperature coefficient of Resistance (TCR) to evaluate the temperature.

The device has been produced with a standard SOI CMOS technology, with the tungsten resistors embedded in a layer of silicon dioxide above the silicon wafer. The whole structure is covered with silicon nitride to protect the device from the atmospheric impurities. A deep Reactive Ion Etching (DRIE) is then used to improve the thermal insulation from the active element to the environment obtaining a 1.2 mm Ø membrane underneath the resistors. After a dicing step, the chip is glued to a gold plated substrate using a metal-based die attach.

When placed in stagnant air, the temperature profile obtained inside the membrane is symmetric, and the measured resistance is the same for the couples R1-R5 and R2-R4. An external flow applied above the chip has two effects. First, the heat removed from the chip will increase, reducing the temperature in the heater and thus the voltage across it. Second, the temperature profile will become asymmetric, as the flow will tend to transport more heat toward the downstream resistors (R4 and R5). The flow direction can be detected with a differential measure on the lateral resistors, whereas it is undetectable from the voltage on R3.

3. 3-D Model

The model has been created using Comsol Multiphysics 4.4, that has the capability to couple analysis performed on a structure in different physical domains. All of the physical aspects have been included in the model: joule heating for the electrical power dissipation and heat transfer via both conduction and convection (natural in stagnant air, forced when the flow is included).

![Fig. 1](image-url) – (a) optical micrograph of the SOI CMOS wall shear stress sensor chip. (b) Schematic diagram showing the sensor cross section (not to scale).
The model includes, together with the chip, the air volumes above and below the active region. Furthermore, die attach and package has to be included since they add a non-negligible thermal resistivity (22W/K) in series on the heat dissipation path, with an important effect (up to 10%) on the temperature profile inside the structure.

Some approximations and assumptions are required in order to contain the mesh count in the model (directly related to the computational time):

- All of the pads are neglected: they are above the substrate where the temperature is assumed constant;
- The structure has a symmetry plane along this mid-point parallel to the flow. Therefore with the proper boundary conditions on the cutting plane only half of the structure needs to be modelled.

The final structure can be seen in Fig. 2a, and the chip (without air volume and packaging elements) in figure 2b. The last critical point to consider is the definition of the boundary conditions:

- For the electric domain, the external surface of all the tracks is defined as ground (reference for the voltage) and a current density is applied on the opposite edge.
- For the thermal domain, the environmental temperature has to be fixed as reference in the structure, the surfaces considered here are the bottom of the package and the flow entrance surface.
- The last domain is the fluid-dynamic, and the conditions applied in this case are: velocity fixed in the entrance and the top surfaces with a parabolic profile, and no slip (null velocity) at the bottom surface.

4. Numerical Results and model validation

The numerical results has been compared with the experiments to validate the model. Figure 3a compares the temperatures in the five elements for 3 different values of current (6.5, 8.5 and 10mA) and wall shear stress ranging from 0 to 0.3Pa shows a good agreement between numerical data and experimental results (an error lower than 5%). The electric output has also been validated, considering both the change in the voltage across the heater (anemometric approach, Fig. 3b) and the differential voltage in the resistor couples R1-R5 and R2-R4 (calorimetric approach, Fig 3c). Those results demonstrate the capability of the model to accurately describe the steady-state device behaviour for different input power levels and wall shear stress in the analysed range.

Fig. 2 – 3-D view of the structure included in the model, complete (a) and without air and packaging elements (b)

Fig. 3 – Comparison between numerical and experimental data: temperature profile for a biasing current of 10mA and different wall shear stress values (a); output voltages for the anemometric (b) and calorimetric (c) configurations as a function of the wall shear stress. Lines identify the numerical data, markers are for the experimental data point.
5. Transient Analysis

The comparison described above demonstrates that the numerical model gives an excellent reproduction of the device. Thus, the numerical results can be used to perform analysis that cannot be easily done experimentally.

A transient analysis has been performed to determine the “turn on time”, defined as the time required for the temperature to go from the 10 to the 90% of the steady state value. The simulation included a step change in the biasing current without any fluid motion, and the value obtained is 44ms. Figure 4 shows the average temperature in R3 from the environmental one to the steady state.

This value is higher than in other devices reported in literature, and two possible reasons can be found for that:

- The high membrane diameter dramatically increases the response time;
- The constant current (CC) driving mode, chosen for its simplicity, requires a longer time than the constant temperature (CT) one to reach the steady state.

This parameter can be used to configure another driving system, with a pulsed current signal. The pulses have to be longer than the rise time to reach the steady state temperature profile; in this way the performances can be preserved with a consistent reduction in the power consumption (depending on the duty cycle, and as high as 50%).

6. Conclusions

The TCAD model presented in this paper has proven to give an accurate description of the CMOS thermal flow sensor, despite the approximations introduced to reduce the mesh count.

The device is based on a tungsten thin wire heater embedded within a thin SiO₂ membrane and fabricated in a CMOS process. The model was created in COMSOL multiphysics and includes the effect of both device and package. The simulations match very well with the measured results for the steady state temperature profile, and gave the possibility to obtain preliminary results for the thermal transient response.

We believe this model can be used for the evaluation of optimum driving signal in pulsed mode configuration, as well as for improving the device layout to reach the desired performances.

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