3D Multiphysics Model of Thermal Flow Sensors

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Abstract

Introduction: This work describes a 3D model for the analysis of thermal flow sensors coupling together electrical, thermal and fluid-dynamic domains. Thermal flow sensors usually comprise at least one resistive heating element (electro-thermal transducer) and a temperature sensing element (thermo-electrical transducer), which measures the heat imparted from the heating element to the flow.

While a number of thermal flow sensors have been reported in the literature [1], there are few examples of numerical models, however, they do not solve a 3D problem [2] or take into account heat generation and conduction losses [3]. Herein, we couple Joule heating with heat conduction and convection in a 3-D geometry. The model was validated by comparison with experimental results obtained with a fabricated test structure.

Thermal flow sensor test structure: A fluid flow sensor test structure was fabricated in SOI CMOS MEMS technology. The device features a resistive tungsten heater (R3) embedded within a dielectric membrane along with four resistive temperature sensors (R1, R2, R4, R5). For testing purposes, the chip was glued onto a gold plated package by mean of a silver-based adhesive. A schematic cross section of the packaged sensor is presented in Figure 1.

3D multiphysics model: A complete model for a thermal flow sensor has to couple different physical domains: heat generation via joule heating and dissipation via conduction, natural and forced convection. This is obtained by coupling three different interfaces: Electric Current, Laminar Flow and Heat Transfer in Solids. The first interface receives as input the biasing current and evaluate the power density generated, while the Laminar Flow interface evaluates the velocity profile in the structure based on the constrains imposed on the boundaries. Those information are both used as input for the third interface, obtaining as output the temperature distribution in the structure. Furthermore, the temperature dependence of all the material properties has been included. Figure 2 reports the 3-D geometry (a) and the device top view (b).

Model validation: First, the flow sensor was characterized in stagnant air. The electro-thermal behaviour of the device is presented in Figure 3, where the temperature of the tungsten resistors is plotted as a function of the power dissipated by R3 via conduction and natural convection. Secondly, the flow sensor was calibrated for different values of wall shear stress. The effect of the forced convection on the temperature distribution on the surface of the device is presented in Figure 4. In both cases our model is able to accurately capture the behavior of the device.

Conclusion: A 3D multiphysics model was developed for the analysis thermal flow sensors. It couples three different physics domains and is able to accurately predict the device behavior, providing engineers with a powerful tool for optimization and fast prototyping of thermal flow sensors.

The model was validated by comparison with experimental results obtained with flow sensor test structure. The temperature profile inside the structure is predicted with extremely high precision in stagnant air (error < 0.5%) and moving air (error < 5%).

Reference

1.N.T. Nguyen, Micromachined flow sensors—a review, Flow measurement and Instrumentation 8.1, 7-16 (1997)
2. Q. Lin et al., MEMS thermal shear-stress sensors: Experiments, theory and modeling, Technical Digest of 2000 Solid-State Sensor and Actuator Workshop (Hilton Head 2000).
3. P. Fürjes et al., Thermal characterisation of a direction dependent flow sensor, Sensors and Actuators A: Physical, 115.2, 417-423 (2004)

Figures used in the abstract

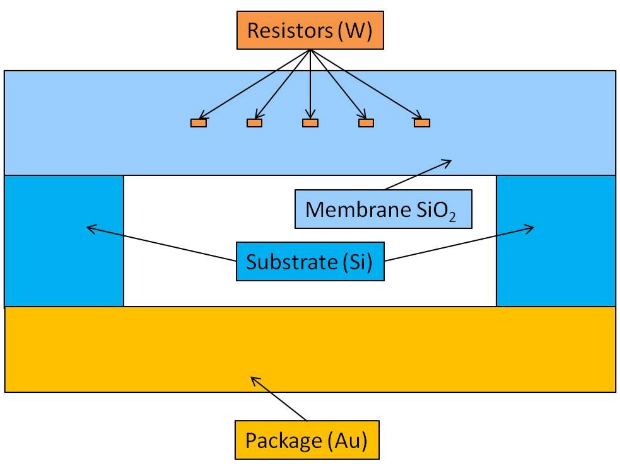

Figure 1: Schematic cross-section of the packaged flow sensor test structure

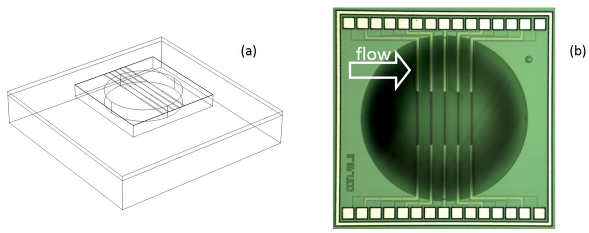

Figure 2: 3-D geometry (a) and optical micrograph (b) of the simulated flow sensor test structure

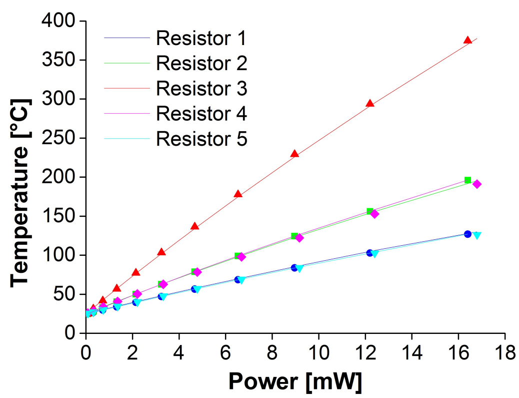

Figure 3: Resistors' average temperature as a function of DC power consumption of the central resistor, R3 (lines for the numerical results, markers for the experimental data points)

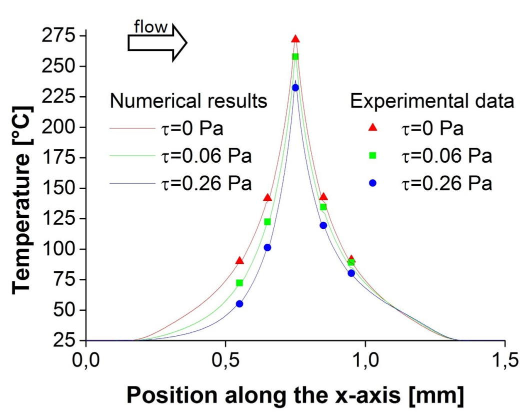

Figure 4: Temperature profile on the device surface for different values of the wall shear stress and heater driving current of 10mA