Sensors and Actuators A 206 (2014) 171–177

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Automatic compensation of pressure effects on smart flow sensors in the analog and digital domain☆

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ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form 1 November 2013
Accepted 11 November 2013
Available online 20 November 2013

Keywords:
Smart sensor
Thermal flow sensor
Pressure compensation
Micro-electro-mechanical systems (MEMS)

ABSTRACT

Two different approaches for the automatic compensation of pressure effects on thermal flow sensors are investigated. One approach operates in the analog domain and it is based on a closed-loop circuit that uses a pressure dependent signal to keep the sensor output constant. The digital approach operates in an open loop fashion and is capable of producing also a pressure reading. The effectiveness of the proposed methods has been verified by means of a smart flow sensor integrating on the same chip the sensing structures and a configurable electronic interface performing signal reading and non idealities compensation. The chip has been designed with a commercial CMOS process and fabricated by means of a post-processing technique. The experimental results performed in nitrogen confirm that both methods are capable of reducing the sensitivity of the flow sensor output signal to pressure variations.

1. Introduction

Measurement of gas flow rate is an essential requirement in many application fields including automotive and process industry, indoor climate control and biomedical instrumentation. Different solutions have been proposed and many commercial products are available in the market. The advent of the MEMS (micro-electro-mechanical systems) technology in the late 1980s paved the way to the design and fabrication of novel micrometric devices characterized by low power consumption, fast response times and reduced weights [1–4]. Micromachined flow sensors based on a thermal principle are without doubts the most investigated devices and a few commercial products are now available. One of the reasons of their success is that the sensor structure is quite simple and can be fabricated adding a few steps to a standard microelectronic process. This allows integrating on the same chip both the sensors and the read-out electronics with advantages in terms of immunity to electromagnetic interferences [5–7]. The increasing sophistication of micromachining technology has stimulated the integration of different sensors on the same chip in order to extract simultaneously different flow parameters, a requirement that is essential to attain accurate measurements. The integration of flow and pressure sensors on the same silicon chip was demonstrated by [8]; nevertheless this result was obtained by combining different technologies, with the drawback of added costs and fabrication complexity. Multi-parameter measurements based on a single sensing structure have also been proposed [9,10].

The dimensions of the sensing structures in the micrometer range introduce also some drawbacks including sensitivity to gas rarefied effects even near the atmospheric pressure [11]. This property has been advantageously exploited to fabricate miniaturized Pirani-type vacuum sensors with measurement range around atmospheric pressure [12]. Nevertheless, pressure sensitivity causes inaccuracy in applications where the flow sensor has to operate in sub-atmospheric ranges like in the gas lines of semiconductor process chambers [13]. Typical compensation schemes use an additional sensor to read the pressure and calculate the correction to be applied to the flow rate sensor output.

Recently we have developed a novel method to obtain information of the gas pressure from the same sensing structure used for flow detection [14]. The method has been developed for thermal flow sensors based on the well known differential microcalorimeter principle. These sensors typically consist of a heater symmetrically placed between two temperature sensors. While the flow-sensitive signal is proportional to the temperature difference between the two temperature sensors (differential signal), a second signal, proportional to the mean of the overheating of the two temperature sensors (common mode signal), can be extracted from the sensor. We observed that the common mode signal can be used to detect the gas pressure for compensation purposes. An all-analog approach based on this principle has been developed and validated by means of a purposely built circuit, implemented with discrete components on printed circuit board (PCB). Recently, we

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☆ Selected Paper based on the paper presented at The 17th International Conference on Solid-State Sensors, Actuators and Microsystems, June 16–20, 2013, Barcelona. Spain

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http://dx.doi.org/10.1016/j.sna.2013.11.013

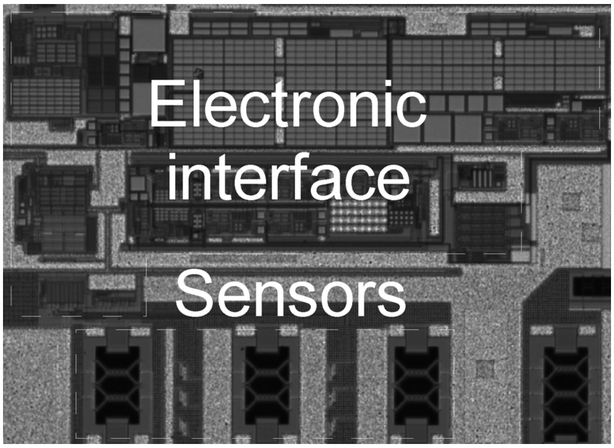


Fig. 1. Photo of the chip area including the electronic interface and the sensing structures after the post-processing.

have developed a single chip solution, consisting in a smart flow sensor with a low-noise-on-chip electronic interface implementing the proposed pressure compensation [15]. This smart sensor uses dual heater sensing structure to obtain also cancelation of the sensor offset and offset drift with the approach described in [16].

In this work, we describe the result of experimental tests performed on this single-chip smart sensor in nitrogen flow, demonstrating the effectiveness of the pressure compensation capability of the interface. We also propose an alternative solution, consisting in processing the two signals (differential and common mode) produced by the sensor using a numerical algorithm. Experimental results shown in this paper demonstrate that, with this "digital" approach, it is possible to produce accurate measurements of both the gas pressure and flow rate from a single sensing structure.

2. Device description and fabrication

The chip has been designed with the BCD6s process of STMicroelectronics and a post-processing technique has been applied to thermally insulate the sensing structures from the substrate. In Fig. 1 an optical micrograph of the chip area including the sensors and the electronic interface is shown. Details about the chip design and fabrication have been reported in [15]. A brief description of the sensors, the electronic interface and the device packaging is reported in the following sections.

2.1. Sensors

The sensors consist of two heaters placed between an upstream and a downstream temperature probe. The heaters are polysilicon resistors placed over suspended dielectric membranes while the temperature probes are thermopiles formed by 10 n^+poly/p^+poly thermocouples. The hot contact of the thermocouples is placed at the tip of a cantilever beam while the cold contact is over the silicon substrate. An optical microscope micrograph of a sensing structure is shown in Fig. 2(a).

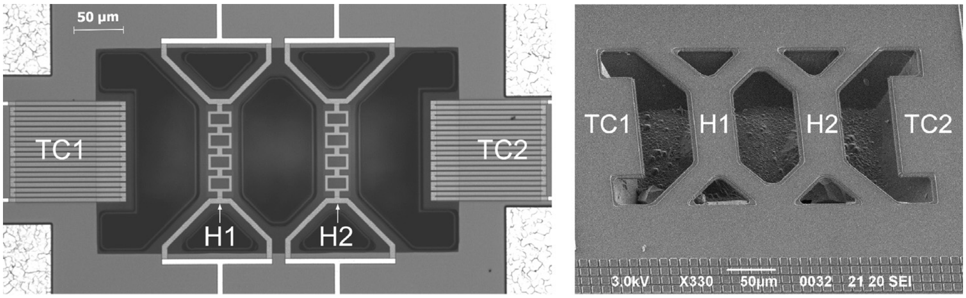
The detection principle is similar to that of conventional calorimetric flow sensors: the thermopiles individually measure the downstream and upstream overheating of the cantilever tips, produced by the heat flux from the heaters; the gas flow produces an asymmetry in the temperature distribution, which is sensed by the thermopiles. The output voltage of the sensor is the difference between the voltages V_{T1} and V_{T2} produced by the two thermopiles and proportional to the upstream and downstream overheating, respectively. The adoption of double heater architectures allows intrinsic offset compensation by means of the power unbalance of the two heaters [16].

The post-processing procedure used to fabricate the sensors consists in two main steps: (i) the selective removal of the passivation and inter-metallic dielectric layers to access the bare silicon from the chip front-side and (ii) the silicon anisotropic etching. The dielectric layers have been selectively removed by means of a photolithographic step followed by a silicon dioxide reactive ion etching (RIE) in CF_4/Ar (50%/50%) gas mixture. The silicon substrate has been anisotropically etched in a solution of 100 g of 5 wt% TMAH with 2.5 g of silicic acid and 0.7 g of ammonium persulfate. Due to the selectivity of this solution toward silicon dioxide and aluminium, no additional masks have been used to protect integrated microelectronic circuits and pads during the etching.

The SEM (scanning electron microscope) micrograph in Fig. 2(b) has been acquired after the silicon etching at 85 °C for 105 min. The visible cavity in the silicon guarantees the thermal insulation of both the heaters and the hot contacts of the thermocouples from the substrate. Thermopile and heater morphology is not visible since they are buried under a thick SiO_2 dielectric layer.

2.2. Electronic interface

The on-chip interface is a versatile system that is capable of performing several operations. A simplified block diagram is shown in Fig. 3, where also connections to a sensing structure is represented. A programmable heater driver produces the two currents I_{H1} and I_{H2} required to bias the sensor heaters. The mean value of the two currents is proportional to the output voltage of the error amplifier, while the current ratio I_{H1}/I_{H2} is programmable through an 8 bit digital word (offset null). Current ratios different from 1 introduce a power unbalance between the heaters that, once properly calibrated, cancels the sensor offset. This approach presents the



(a) (b)

Fig. 2. Optical microscope (a) and SEM (b) image of a double heater structure after the silicon removal in a TMAH solution (H1, H2: heaters over suspended SiO_2 membranes; TC1, TC2: thermopiles).