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ScienceDirect

Procedia Engineering 168 (2016) 757 – 761

Procedia Engineering

www.elsevier.com/locate/procedia

30th Eurosensors Conference, EUROSENSORS 2016

A compact, dual channel flow-based differential pressure sensor with mPa resolution and sub-10 mW power consumption

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Abstract

In this work, we propose a single-chip sensor for the detection of two extremely low, independent differential pressures. The operating principle consists in measuring the airflow induced by the pressure through a channel of sub-millimeter cross-section [1]. The airflow is measured by differential thermal flow sensors, implementing a recently proposed drift-free offset compensation approach. Use of a low-noise, low-power readout interface, integrated on the same chip as the sensing structures, allowed the achievement of resolutions of 1.29 mPa, which are one order of magnitude lower than state-of-art devices. This performance has been obtained with power consumptions suitable for battery-powered applications.

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Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference

Keywords: Differential pressure sensor, high reseolution, Dual channel, System on a Chip

1. Introduction

Monitoring of small pressure differences is a frequent requirement in air conditioning systems, low volume exhaust gas ducts and for precise determination of wind speed and direction [1]. Critical applications, such as monitoring respiratory activity [2], urge the development of differential pressure sensors with sub-1Pa resolutions. Membrane-based sensors that can detect pressure differences in the mentioned range or below are generally rather bulky and not suitable for integration on a silicon chip. Resolutions of 0.5 Pa have been envisioned by means of simulations for MEMS pressure sensors [3], while the performances reached by commercial devices are typically

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Peer-review under responsibility of the organizing committee of the 30th Eurosensors Conference
doi:10.1016/j.proeng.2016.11.272

one order of magnitude worse. Recently, a method to detect very small pressure differences by measuring the airflow induced by the pressure itself through a narrow channel has been described [4]. Indeed, the most sensitive commercial products actually exploit the mentioned principle. The drawback is clearly the leakage introduced by the flow channel, which limits the use of these sensors to situations where the pressure difference is continuously regenerated. This condition is satisfied in most applications where the target is monitoring the properties of a flow or airstream. Even in these cases, it is important to keep the leakage to a minimum by using very narrow flow channels in order to reduce the perturbation introduced by the sensor. In this work, we propose a differential pressure sensor based on a recently proposed single-chip, multi-sensor platform [5]. Using a low cost packaging procedure [6], two independent flow channels are routed to the chip surface, allowing simultaneous measurement of two differential pressures with a single, ultra-compact device. Measurement demonstrated that resolutions as low as 1.2 mPa can be obtained with the proposed approach.

2. Device description

Fig. 1 (left) shows a photograph of the sensing chip, designed and fabricated using the BCD6s process of STMicroelectronics and finished with a simple post-processing micromachining step, aimed at providing thermal insulation. The chip includes several distinct sensing structures, all based on thermal principles. The flow sensing structures used in this work for differential pressure sensing are indicated with S2 and S3 in the figure. Each structure consists of two thermopiles placed across two heaters, lined up along the flow direction. According to the well-known operation of differential micro-calorimeters, a flow shifts convective heat towards the downwind thermopile, producing a temperature difference that is converted into a voltage. The double-heater configuration have been introduced to implement an offset compensation approach [7] that effectively reduces also offset variations due to changes in the gas temperature and pressure.

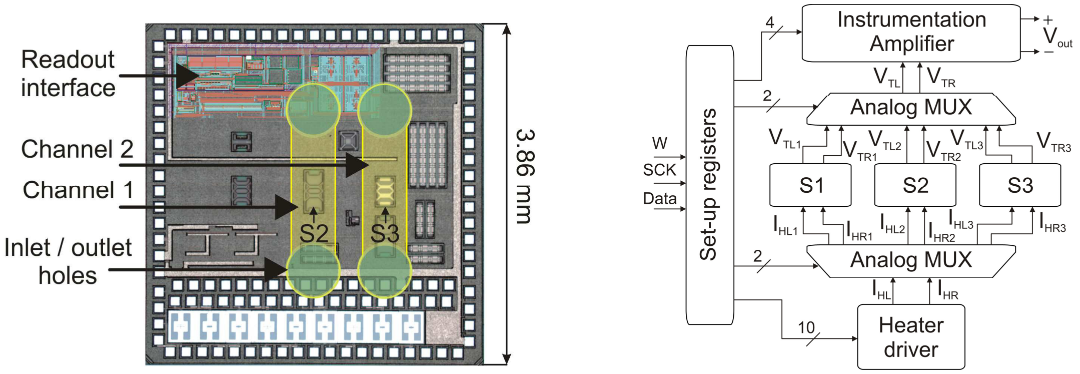

Fig. 1 (Left) Photograph of the chip before post-processing: the two sensing structures, S2 and S3, used in this work are indicated. The layout of the readout interface has been superimposed on the area covered by planarization dummies for clarity. The footprint of the two channels with the inlet/outlet holes is highlighted. The channel cross-section was 0.5 x 0.15 mm^2. (Right) Equivalent block diagram of the integrated interface.

A complete analog readout interface is integrated into the same chip as the sensors. A block diagram of the interface is shown in Fig. 1 (right), where connection to three on-chip sensing structures by means of analog multiplexers is represented. A programmable current source, indicated as heater driver in the block diagram, is used to feed the heaters with currents whose common mode value sets the sensitivity, while the differential one is tuned to compensate for the sensor offset [7]. The voltage produced by the thermopiles is read by a chopper stabilized instrumentation amplifier (gain =200). The interface parameters are controlled by a set of digital registers that can be programmed through an SPI-like communication line. The chip are glued to a 2-cm circular printed circuit board (PCB) and connection from the chip pads to the PCB tracks is obtained by means of wedge bonding. Gas flows are conveyed to the sensing structures by means of a poly-methyl-methacrylate (PMMA) adapter provided of a small coupling surface (3 x 3 mm^2) where two trenches are milled [6]. The adapter-coupling surface is placed in contact with the chip front face, which seals the trenches, thus forming the channels. The trenches are accessed by holes that end on the opposite face of the adapter, which is properly enlarged to allow insertion of stainless-steel needles. Manual alignment of the adapter to the chip is performed with the aid of an optical microscope. The final device, together with a ruler with units in centimeters, is shown in Fig. 2. Silicone pipes are used to connect the inlet / outlet needles to the measurement line.

The same platform was used for the flow sensor described in Ref. [5] where more details on the post-processing steps are reported. In order to reduce leakage, the original 0.5 mm trench depth used in Ref.[5] is reduced to 0.15 mm for the sensors described in this work. The trench width, equal to 0.5 mm, was not reduce with respect to Ref. [5] since it was necessary to maintain a sufficient margin from the structures and the trench wall during the alignment phase.

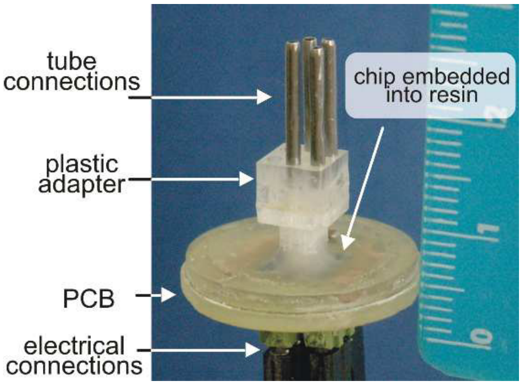

Fig. 2. Photograph of the assembled device. A plastic adapter (gas conveyor) was aligned to the chip and fixed with cyanoacrylate resin. The chip is supported by a printed circuit board (PCB). Ruler units are centimeters.

3. Experimental results

The output voltage of the amplifiers was read by an external PCB board equipped with high resolution Delta-Sigma ADCs, (Analog Devices ADuC847) controlled by a personal computer. The acquired data-stream was low-pass filtered with a cut-off frequency of about 10 Hz. Fig. 3 shows the response of the two sensor channels to differential pressures measured in a reference line. The air flow-rate through the channels is shown in Fig. 4, as a function of pressure. Excellent matching between the two channels can be observed. Differences in the responses of Fig. 3 are due to different design choices for the flow-sensitive structures. In particular, S3 is optimized for the best sensitivity / power consumption tradeoff [5], while S2 for the smallest residual offset.

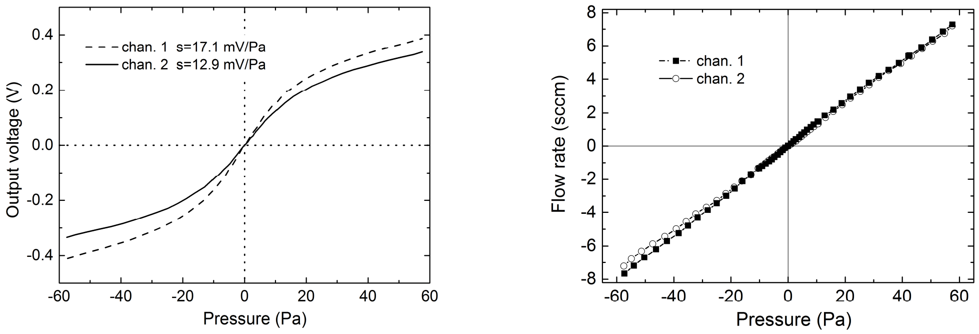

Fig. 3. (Left) Response of the two sensing structure as a function of pressure. The sensitivity, s, has been calculated with a linear fitting near the axis origin. Sensing structures S2 (chan. 1) and S3 (chan. 2), which have different design parameters, are driven with different current levels. (Right) Flow rate as a function of the differential pressure for both channels.

In order to obtain similar sensitivities, S2 and S3 structures have been driven with different heater currents (0.5 mA and 0.32 mA, respectively). Power consumption is 4.0 mW when S2 is selected and drops to 2.6 mW when S3 is used. (left). The output peak-to-peak noise of the system, measured with a zero differential pressure, is 120 μV. With the sensitivities estimated from the data of Fig. 3, the corresponding equivalent pressure noise is 7.0 and 9.3 mPa for S2 and S3, respectively.

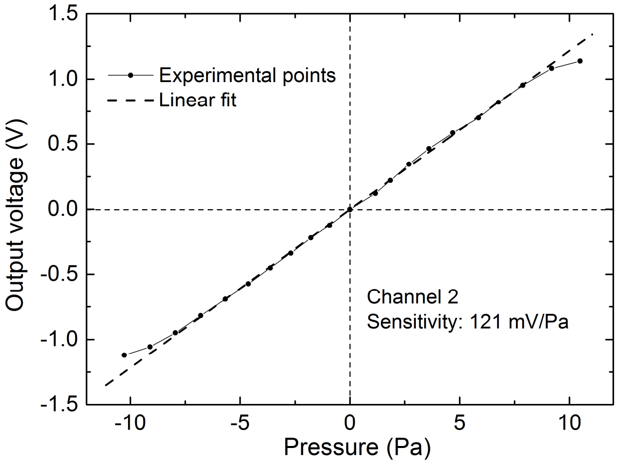

Fig. 4. Measured flow rate in the channels as a function of pressure. The good matching between the two curves confirms that the two channels milled on the conveyor surface are almost identical.

The best resolution that can be achieved by the proposed device is obtained by driving the heaters of the most sensitive structure (S3, channel 2) with a current of 1 mA, which coincides with the maximum output current of the on-chip source. The result shown in Fig. 4, demonstrate that a nearly tenfold sensitivity increase can be obtained. The output noise was only marginally increased from 120 mV to 157 mV, probably due to increased contribution from the current source. Considering the sensitivity reported in Fig. 4, the equivalent pressure noise is 1.29 mPa, obtained with a total power consumption of 7.3 mW.

Acknowledgements

The authors would like to thank the R&D group of the STMicroelectronics of Cornaredo (MI, Italy) for fabrication of the sensor chip.

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