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Highly Sensitive Smart Flow Sensor with Frequency and Duty Cycle Output

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Abstract

A thermal flow sensor with smart electronic interface is presented. The sensor is based on four germanium thermistors embedded in a thin membrane. The thermistors form a Wheatstone bridge supplied with a constant current. Both bridge output voltage and voltage at the bridge supply terminals are functions of the flow offering high initial sensitivity and wide measurement range, respectively. The signal interface is based on a relaxation oscillator. The circuit provides a rectangular-wave output whose frequency is related to the bridge unbalance, whereas the duty cycle is a function of the voltage at the bridge supply terminals. Hence, both sensor signals are simultaneously and independently carried on the same output signal, featuring non-monotonic characteristic over a wide flow range accompanied with a very high sensitivity at low flow velocities. Moreover, as the circuit excites the bridge with a constant current, the connection of remote sensors without accuracy degradation is possible.

Keywords: thermal flow sensor; smart sensor interface; resistance-controlled oscillator.

1. Introduction

Micromachined thermal flow sensors based on a self-heating thermistor-array combine advantages of the calorimetric and the hot-film flow sensors [1]. The thermistors, arranged in a Wheatstone bridge configuration, act as heat sources and as temperature sensors simultaneously. Two output characteristics related to the flow are available: the bridge unbalance and the overall resistance across the bridge supply terminals, offering high initial sensitivity and wide measurement range, respectively. Moreover, the total dissipated power is in the sub-mW range making them suitable for microfluidic measurements in, e.g., biomedical applications.

In order to provide both characteristics in a single output signal, a smart electronic interface was applied. The circuit is based on a relaxation oscillator with current excitation of the sensor bridge and a rectangular-wave output. Its frequency is related to the bridge unbalance, whereas the duty cycle is a function of the voltage at the bridge

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supply terminals, i.e. the bridge resistance. Thus, it is possible to carry simultaneously both sensor signals on the same output signal without degrading the sensor characteristics. Moreover, the sensor excitation with a constant DC current is advantageous for remote sensing applications [2].

2. Thermal flow sensor

Figure 1 depicts the membrane layout of the flow sensor. The device is based on four thin-film germanium thermistors embedded in the silicon-nitride membrane. The sensor membrane consists of the SiO_2 and Si_3N_4 wafer coating and the passivation layer SiN_x, featuring 250 nm, 70 nm, and 1250 nm thickness, respectively. The central heater is not used and the two substrate thermistors (ST1, ST2) measure merely the fluid temperature, which is in our measurement setup equal to the ambient temperature. The active elements are the four membrane thermistors ($R_{th,1\text{-}4}$) placed symmetrically to membrane midpoint at the distances of 75 µm and 150 µm, respectively. Each of them consists of a 260 nm thick germanium film, which is contacted by four metal strips (Ti-Au-Cr sandwich) exhibiting a total thickness of about 270 nm. The thermistor resistance is typical about 80 kΩ at ambient temperature and the TCR (Temperature Coefficient of Resistance) of about -2 %/K of amorphous germanium enables high temperature sensitivity [3]. The sensor membrane features an overall size of about 0.5 x 1 mm^2 and is suspended over a 350 µm thick micromachined silicon frame.

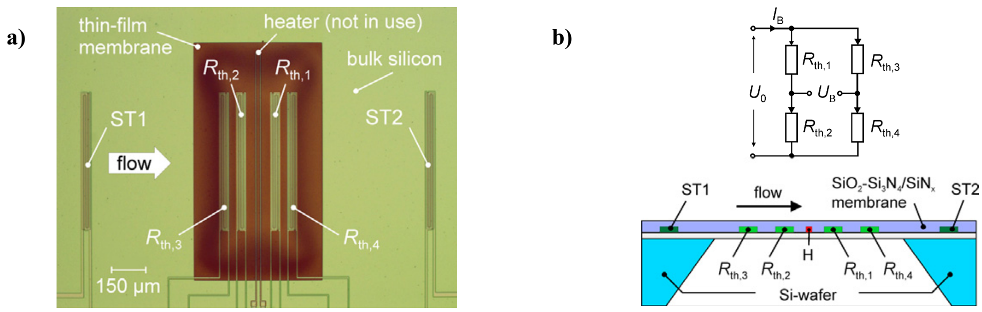

Fig. 1. (a) Photomicrograph of the flow senor chip. The overall chip size is 3 × 6 mm^2, the size of the membrane is 0.5 × 1 mm^2. Membrane thermistors ($R_{th,1\text{-}4}$) operate as active heating and sensing elements, substrate thermistors (ST1 and ST2) measure the ambient temperature; (b) Schematic cross section of the flow sensor with a Wheatstone bridge comprising four membrane thermistors. The bridge is supplied with constant current I_B. The heater H is not in use.

The thermistors are connected to form a Wheatstone bridge supplied with a constant DC current. Due to self heating, the thermistors operate simultaneously as heat sources as well as temperature sensors. The cross section of the flow sensor and the position of the thermistors are shown in Fig. 1b. In this configuration both the bridge unbalance voltage U_B and voltage at the bridge supply terminals U_0 are functions of the flow.

The bridge unbalance voltage U_B features a bidirectional characteristic. Due to higher initial relative sensitivity, it is the preferred output quantity for low flow velocities. However, the non-monotonic characteristic limits the useful flow to a few m/s only. In contrast, the voltage at the bridge supply terminals U_0 offers a wider measurement range though with unidirectional characteristic and a lower relative sensitivity [1]. Due to low supply current of 40 µA, the overall power dissipated in the sensor is approximately 130 µW. Thus, the heating of passing fluid is negligible which can be crucial for measuring the fluids that endure only slight temperature elevations.

3. Electronic interface

The complementary advantages of both sensor readouts U_B and U_0 can be unified in a single output signal utilizing a smart electronic interface (Fig. 2). It is based on a relaxation oscillator, where the frequency of the rectangular output wave is proportional to the bridge unbalance voltage U_B and the duty cycle is related to the voltage at the bridge supply terminals U_0. Thus, the two sensor signals are independently and simultaneously carried on the same output signal.

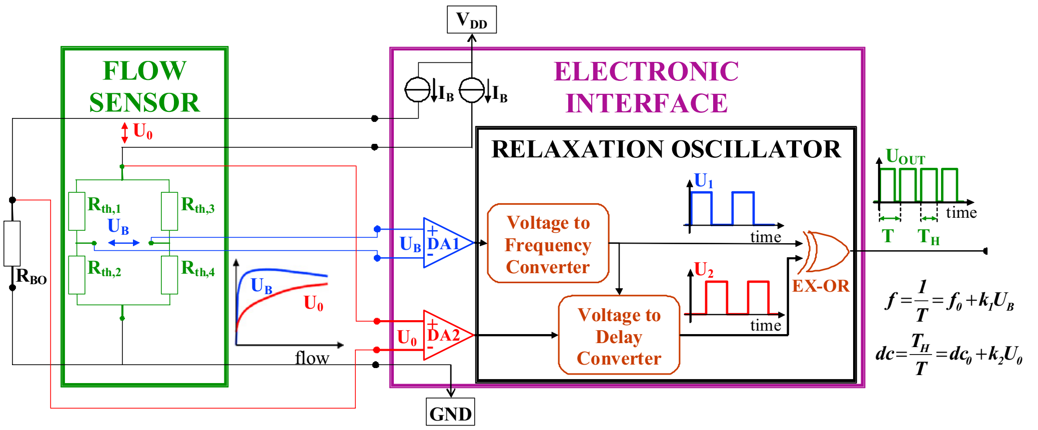

Fig. 2. Block diagram of the sensor with electronic interface and relevant signals. The frequency of U_1 is directly proportional to the bridge unbalance voltage U_B whereas the signal U_2 is phase-shifted with respect to U_1 by an amount depending on the voltage at the bridge supply terminals U_0. Hence, both the frequency and the duty cycle of the output signal are flow dependent according to sensor output characteristics.

$$f = \frac{1}{T} = f_0 + k_1 U_B$$

$$dc = \frac{T_H}{T} = dc_0 + k_2 U_0$$

The electronic interface provides the DC current I_B = 40 μA needed for the bridge supply. The voltage outputs U_B and U_0 are first low-pass filtered and amplified by chopper-input differential amplifiers DA1 and DA2. The frequency of the square-wave voltage U_1 is directly proportional to the bridge output voltage U_B whereas the signal U_2 is phase-shifted with respect to U_1 by an amount depending on the voltage U_0. By applying an EX-OR operation between the signals U_1 and U_2 the rectangular-wave output signal U_{OUT} is obtained. Its frequency f and duty cycle dc are linear functions of U_B and U_0, respectively as shown in equations of Fig. 2. The central frequency f_0 and the frequency sensitivity k_1 were set at about 11.8 kHz and 0.8 kHz/mV, respectively. The duty cycle sensitivity k_2 was set at about 2.6 %/mV, while the value of the resistor R_{B0} sets the value of dc_0 at about 16%.

4. Experimental results

The sensor chip was flush mounted into a milled recess with the surface of a PCB (Printed Circuit Board, Fig. 3a). In order to avoid fluid leakage around the chip, the gap between the sensor chip and the recess walls was sealed with epoxy resin. The bottom of PCB is provided with a pressure-compensation leak, what prevents the membrane destruction in case of large pressure variation. A slit in a thin copper layer laid over the sensor surface forms a rectangular flow channel of 0.5 mm height and 1.2 mm width (Fig. 3b). The channel is covered with a plastic plate with flow inlet and outlet connections. Nitrogen gas flow was established using standard 100 sccm (for average velocity up to 1 m/s) and 2000 sccm (for average velocity up to 25 m/s) flow controllers. With known mass flow rate and cross-sectional dimensions of the channel the average flow velocity can be calculated.

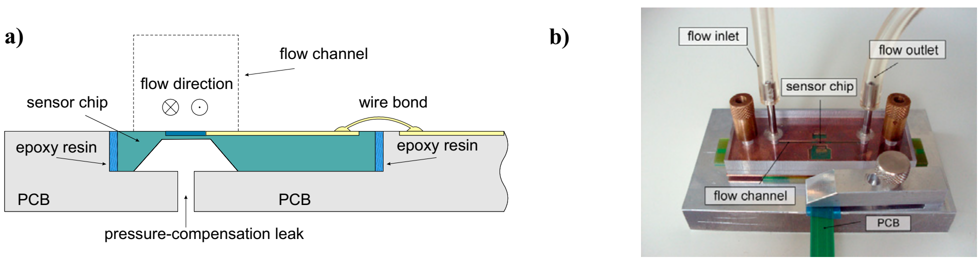

Fig. 3. (a) Schematic cross-sectional view of the sensor mounted on the printed circuit board (PCB); (b) PCB with the sensor chip incorporated in the wall of a miniaturized rectangular flow channel with cross-sectional dimensions 1.2 mm width and 0.5 mm height.

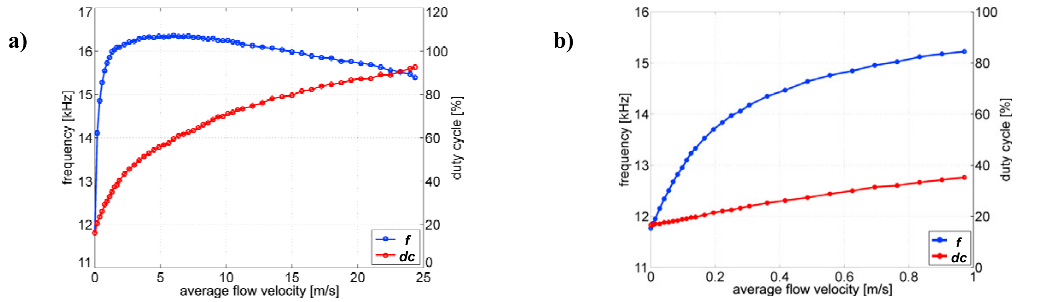

Fig. 4. Measured frequency and duty cycle of the output signal for the wide flow range up to 25 m/s (a) and very low flow range < 1 m/s (b).

The thermistors were arranged in a Wheatstone bridge as indicated in Fig. 1b and connected to the smart electronic interface. The experimental results for the flow in the range 0-25 m/s are illustrated in Fig. 4a. The frequency characteristic of the output signal has a very high relative sensitivity for mean flow velocities below 3 m/s, but for higher flow velocities it saturates and becomes ambiguous. In contrast, the duty cycle of the output signal shows a less sensitive but monotonic characteristic. Combining the frequency and duty cycle outputs it is possible to measure accurately the average flow velocity over a full measurement range. In Fig. 4b the measured frequency and duty cycle of the output signal are depicted for very low flow velocities (< 1 m/s). In this low-flow range the initial sensitivity of the frequency characteristic amounts to about 13.7 kHz/(m/s) with the equivalent resolution of about 0.5 cm/s.

5. Conclusion

A system for flow measurement comprising a micromachined thermal flow sensor and a smart electronic interface is presented. The flow sensor is based on a novel transduction principle that combines advantages of the calorimetric and the hot-film transduction principles. It utilizes the self-heating effect of four thin-film germanium thermistors embedded in a silicon nitride membrane. The thermistors are connected to form a Wheatstone bridge. Both bridge output voltage and voltage at the bridge supply terminals are functions of the flow. The electronic interface is based on a relaxation oscillator. Its output frequency is proportional to the bridge unbalance voltage, while the output duty-cycle depends on the voltage across the supply terminals of the sensor bridge. Thus, two independent pieces of information related to flow are simultaneously and independently carried on the same output signal. The measurement system has been characterized as a function of the average flow velocity of nitrogen gas at room temperature. The output characteristic features high initial sensitivity and a wide flow range up to 25 m/s.

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References

[1] Cerimovic S, Talic A, Sauter T, Kohl F, Beigelbeck R, Schalko J, Jachimowicz A. A Novel Thermal Transduction Method for sub-mW Flow Sensors. *Proceedings of IEEE Sensors 2009*, Christchurch, New Zealand, pp.1325-1328.

[2] Ferrari V, Marioli D, Taroni A. Oscillator-based Interface for Measurand-plus-Temperature Readout from Resistive Bridge Sensors. *IEEE Trans. on Instrum. Meas.*, 49 (3), 2000, pp. 585-590.

[3] Glaninger A, Jachimowicz A, Kohl F, Chabicovsky R, Urban G. Wide range semiconductor flow sensors. *Sensors and Actuators A 85*, (2000), pp. 139–146.