Highly Sensitive Sensor for Flow Velocity and Flow Direction Measurement

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***Abstract*— Miniaturized sensors for flow velocity and flow direction measurement based on thin-film germanium thermistors (TCR = -1.8 % /K) offering extremely high sensitivity were developed. The thermistors are placed on a silicon nitride diaphragm (1.3 µm thick) which is carried by a silicon frame. To resolve the direction of the flow, eight thermistors are arranged circularly on the diaphragm. Two orthogonal pairs of diametrically opposed thermistors (e. g., N-S and E-W) feature a directional sensitivity of 152 µV/deg at a flow velocity of 1 m/s. An increase of the sensitivity of about 50% can be gained by analyzing the difference signal of two 90° rotated thermistors (e. g., N-E), which are in the downstream position. The measurable gas flow rate ranges from 0.025 m/s to about 3 m/s for the constant power mode. The sensor has a high sensitivity to flow direction of 30 mVs/m at low flow rates from 0.025 m/s to 0.2 m/s.**

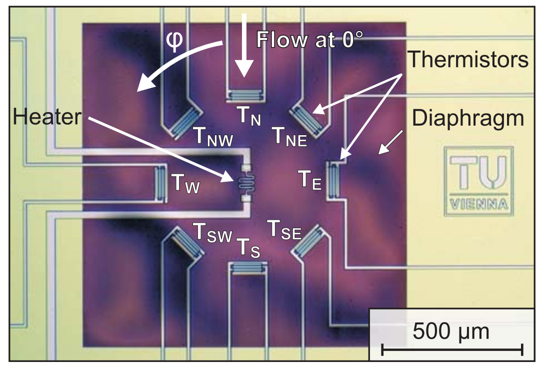

Fig. 1. Photomicrograph of the micromachined flow sensor. φ denotes the direction of the flow with respect to the N-S-direction. The different shading of diaphragm and leads is caused by the buckling of the diaphragm.

I. Introduction

Measuring velocity and direction of fluid flows are very important tasks in various applications. Especially miniaturized sensors are suitable for the investigation of flows with high spatial resolution which are not accessible with mechanical anemometers. The miniaturized cutting-edge devices are based on the calorimetric principle allowing the simultaneous measurement of flow direction and velocity [1, 2]. The high resistive temperature coefficient (TCR) of amorphous germanium thermistors, which are already applied for flow sensor applications [3, 4], initiated the design of extremely sensitive flow direction sensors. Moreover, a further increase of sensitivity was expected by the use of four additional thermistors.

II. Experimental

A. Sensor

The sensors are realized on $\langle 100 \rangle$-Si wafers, which are passivated on both sides with 250 nm thermal silicon oxide and 70 nm LPCVD (low-pressure chemical vapor deposition) silicon nitride. The heater consists of a chromium meander with a width of 5 µm, a thickness of 130 nm, and a mean length of 310 µm. Its resistance amounts to about 580 Ω. The thermistors are made of a amorphous germanium layer with the extensions of 100 µm × 35 µm and a thickness of 250 nm, which is contacted by an interdigital sandwich structure consisting of 50 nm titanium (at the germanium side), 100 nm gold and 30 nm chromium. This forms a Ge-resistor with a cross-section of 75 µm^2 and a length of 5 µm. The resistance of the Ge-thermistors is typically 320 kΩ. Amorphous germanium was chosen as thermistor material because its resistivity is highly sensitive to temperature changes [5]. It exhibits a TCR of about -1.8 %/K being almost five times higher than the corresponding value of platinum.

The metal layers and the germanium layer have been evaporated and patterned with image reversal photo resists. The sensor structure is passivated by a 1 µm thick LPCVD silicon nitride layer. Afterwards, the diaphragm is created by an anisotropic etching process applying 30 wt% potassium hydroxide solution at 80 °C from the backside of the wafer. The etching process is finished, when the solution reaches the silicon oxide layer, which acts as an etch stop. The resulting diaphragm consists of two silicon nitride layers and one silicon dioxide layer and features an overall thickness of about 1.3 µm and an area of 1.2×1.2 mm^2. It is characteristic

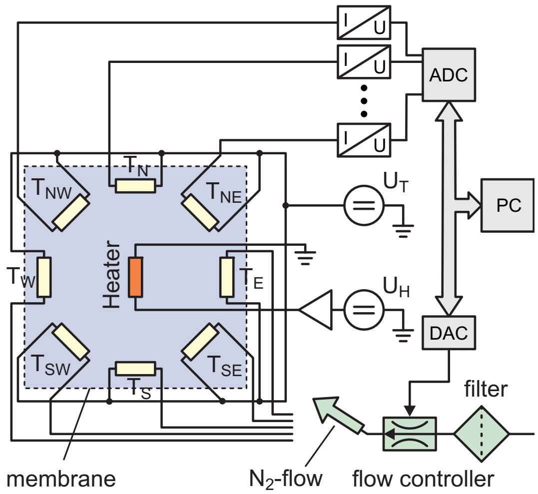

Fig. 2. Schematic measurement setup. T_N, T_{NE}, …, T_{NW} …thermistors, U_N …thermistor voltage, U_H …heater voltage.

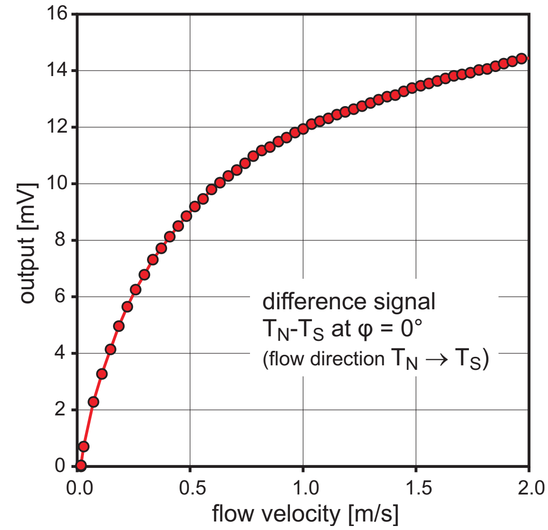

Fig. 3. Difference signal of a pair of diametrically opposed thermistors ($U_{T_N} - U_{T_S}$) versus flow velocity. The channel is oriented in parallel to the connecting line of the thermistors.

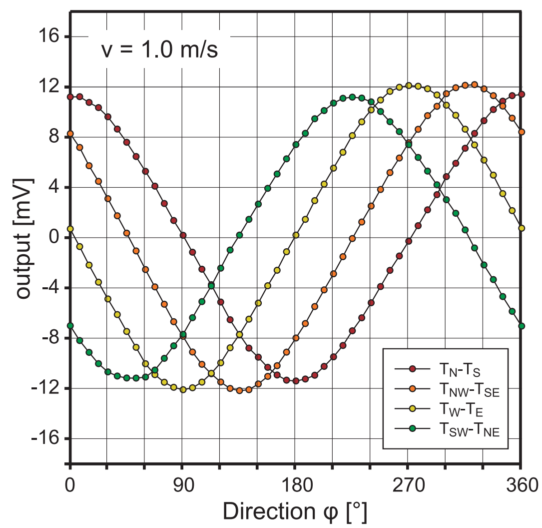

Fig. 4. Difference signals of opposed thermistors versus flow direction. The amplitude of the signals corresponds to a temperature rise of $\approx 1.5\,$K. The maximum sensitivity $S = 152\,\mu$V/deg is obtained when the flow is perpendicular to the thermistor pair (zero-crossing of the curves).

for the anisotropic etching of a $\langle 100 \rangle$-Si single crystal that the boundaries of the etched cavity are formed by $\{111\}$-planes [6]. A truncated pyramid, bounded by the silicon nitride membrane, is thus built. This way of producing a diaphragm is rather simple, but the shape is restricted to rectangular forms.

The sensor device (Fig. 1) comprises eight amorphous germanium thermistors being circularly arranged around a chromium heater. They are all situated on a thin silicon nitride diaphragm. An additional thermistor (not shown in Fig. 1), located on the silicon frame supporting the diaphragm, provides the opportunity of determining the ambient temperature and allows compensation of its influence on the sensor characteristics. The overall dimensions of the chip are $6\,\mathrm{mm} \times 3\,\mathrm{mm} \times 0.35\,\mathrm{mm}$.

B. Measurement setup

The sensor chip is flush-mounted with the bottom of a rectangular flow channel of 12 mm width and 1 mm height. The sensor mounting allows 360° rotation of the channel axes with respect to the sensor orientation. Filtered nitrogen acting as test gas for the flow is fed into the channel 5 cm apart from the sensor (Fig. 2). The velocity of the nitrogen in the channel is adjusted by a mass flow controller having a range of 2000 sccm/min which corresponds to a maximum velocity of 2.8 m/s. The chromium heater is operated at constant voltage ($U_H = 0.5\,$V) dissipating a heat power of 430 µW. This leads to a peak excess-temperature of approximately 5 K. The resistance of the thermistors is measured by applying a constant voltage ($U_T = 5\,$V) and converting the current with a current-to-voltage converter (120 mV/µA), based on the ultralow noise BiFET operational amplifier AD743. The output voltages are recorded by a PC-controlled data acquisition board.

III. Results

The output voltage of a pair of diametrically opposed thermistors versus flow rate is depicted in Fig. 3. The flow direction is parallel to the connecting line of the north and south thermistors. This diagram emphases the high sensitivity of 30 mVs/m of the device at low flow rates. In this operation mode, the characteristic saturates at about 3 m/s. At higher velocities the output even decreases because of the forced convection.

The dependence of the difference signals on the flow direction φ can be seen in Fig. 4. Due to imperfections of the technological processes the individual resistance values of the thermistors vary slightly. This causes an offset of the

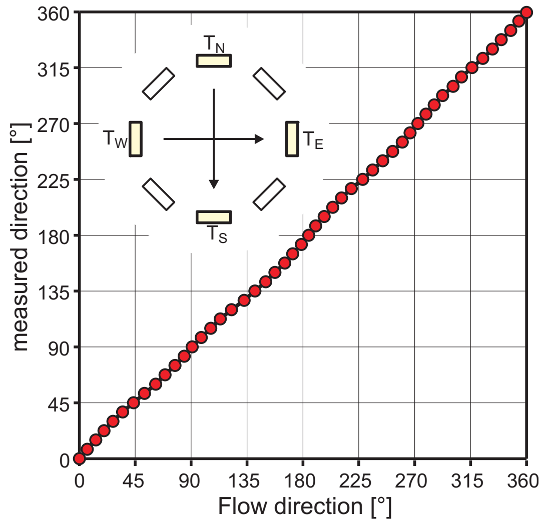

Fig. 5. Measured direction versus flow direction determined by Eq. (1). $v = 1$ m/s.

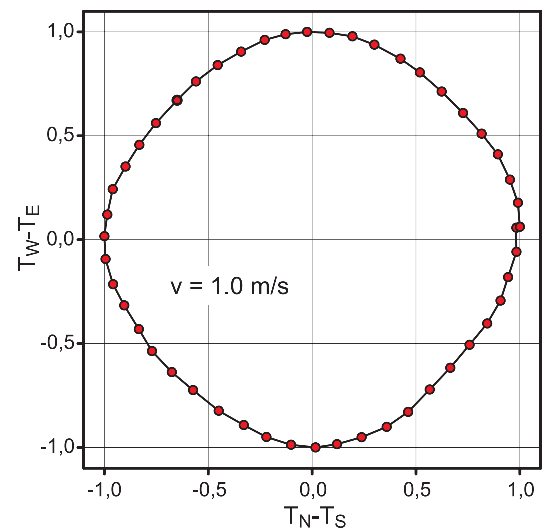

Fig. 6. Example of normalized difference signals of two perpendicular thermistor pairs

difference signals. To eliminate this effect, the signals are made symmetric by shifting the curves by the average of the minimum and maximum values within the measurement cycle. In the region, where the flow direction is almost perpendicular to the thermistor pair, the sensitivity amounts 152 µV/deg. The single response signals exhibit not exactly the same amplitude, because the thermistors' sensitivity varies also slightly.

The flow direction can be determined by using the difference signals of two thermistor pairs. Normally, two pairs which are 90°-rotated are utilized. Assuming a sinusoidal response of the difference signal to the flow direction the angle φ can be calculated by

$$\varphi = \arctan\left(\frac{U_\mathrm{N} - U_\mathrm{S}}{U_\mathrm{W} - U_\mathrm{E}}\right). \tag{1}$$

Considering the signs of numerator and denominator, one can decide the quadrant the angle is lying within. Applying Eq. (1) to the N-S and W-E signals of Fig. 4, the flow direction response can be calculated (Fig. 5).

The directional characteristics of the thermistor pairs in Fig. 4 differ from the ideal sinusoidal shape, they could be better described by a chamfered triangle. Therefore, the measured direction plotted versus the exact values yields no perfect straight line. To illustrate this more clearly, the signal of one pair is plotted against the signal of the orthogonal one in Fig. 6. In the ideal case a circle would be expected. Due to a small temperature drift during the cycle, which has not been compensated, the curve is not closed exactly (data points at the outmost right position).

The resolution of the flow direction can be enhanced by evaluating the difference signal of two thermistors which are arranged in a 90° angle around the heater, e. g., the north and east thermistors (Fig. 7). The sensitivity obtained by such a pair is 225 µV/deg when it passes the downstream position. This value is about 50% higher than that of an orthogonally arranged thermistor pair.

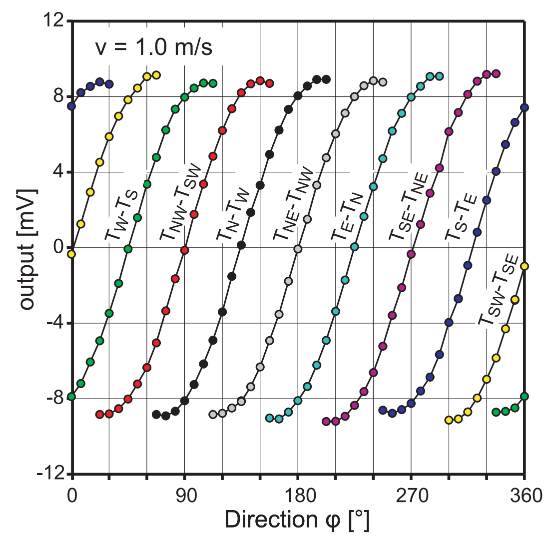

Fig. 7. Difference signals of thermistor pairs versus flow direction. The thermistors are arranged in a 90° angle around the heater. The maximum sensitivity $S = 225$ µV/deg.

IV. Conclusion

For a sensor device which should have an axially symmetric characteristic it is evident that the sensor design should also be axially symmetric. For this reason other researchers use sophisticated designs where the meander of the heater fills a central circle and the thermistor structures surrounding the heater occupy 90°-sectors [7]. To get a straightforward design and due to the fact that the applied thermistors and heater are small compared to the membrane extensions, no special distributed elements are used. In the present design, the quadratic footprint of the diaphragm leads to thermal conductance which depends on the direction. The distance of the thermistors from the thermally well-conducting Si-frame is smaller in the N-direction (0°) than in the NW-direction (45°). Therefore, the N-thermistor is less heated by the airflow than the NW-thermistor which is thermally less coupled to the Si-frame. From the operational point of view the situation is completely symmetric as long as orthogonally arranged thermistor pairs are used (e. g., N-S and W-E).

The sensor device allows gas flow measurements in the range from 0.025 m/s to about 3 m/s (Fig. 3). Its upper limit can be extended by at least one order of magnitude if the heater is operated in the constant over-temperature mode. Due to the higher flow rates, the heater is more efficiently cooled and more heating power can be applied.

In the present contribution it could be shown that amorphous germanium as sensitive thermistor material is well-suited for highly sensitive sensor devices to measure gas velocity as well as flow direction. The use of thermistor pairs, which are arranged in a 90° angle around the heater, enable a 50% improvement in the sensitivity for flow direction.

Acknowledgment

The authors would like to thank E. Svasek and P. Svasek from the Institute of Sensor and Actuator Systems, Vienna University of Technology, for dicing and bonding the devices, respectively. This work was financially supported by the Austrian Research Promotion Agency (FFG), Project 810220 which is gratefully acknowledged.

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