Sensitive Measurement of Flow Velocity and Flow Direction Using a Circular Thermistor Array

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Eight highly sensitive amorphous germanium thermistors (TCR = -1.8%/K) are the sensitive part of the micromachined sensors for flow velocity and flow direction. Carried by a 1.3 µm thick diaphragm they measure temperature differences generated by the sample flow and a heater (430 µW). This allows gas flow measurements in the range from 0.025 m/s to about 3 m/s with a sensitivity of up to 30 mV/(m/s). Two orthogonal pairs of opposed thermistors feature a sensitivity of 150 µV/°. An increase in sensitivity (50%) is gained by using two 90° rotated thermistors situated in the downstream position.

Introduction

Measurement of fluid velocity combined with the acquisition of flow direction is a challenging task in different fields of research. Especially miniaturized sensors are suitable for investigation of flows with high spatial resolution which are not accessible for mechanical anemometers. The current miniaturized cutting-edge devices are based on the thermal anemometer principle allowing the simultaneous measurement of flow direction and velocity [1]. The application of amorphous germanium thermistors for flow sensor [2] with their high resistive temperature coefficients (TCR) initiated the design of extremely sensitive flow direction sensors. Moreover, a further increase in sensitivity of the direction measurement was expected by the use of four additional thermistors.

Sensor Principle

Basis of the sensor is the so-called ‘calorimetric’ measurement principle where a thin diaphragm supported by a micromachined silicon frame is flush mounted with the wall surrounding the flow channel. A thin-film resistor (heater) at the centre position of the diaphragm generates a symmetric temperature distribution on the diaphragm as long as the flow velocity is zero. When a tangential flow occurs, the thermal symmetry is broken. Two thermistors, placed symmetrically in respect to the heater and parallel to the flow, are used to measure the temperature difference. More heat is transported to the downstream thermistor than to the upstream ones, a difference signal is generated which is a measure for the velocity. Applying more than one thermistor pair on the diaphragm being rotated appropriately compared to the first one, the direction of the flow within the diaphragm plane can be measured.

For high sensitivity the diaphragm has to have a high thermal resistance. The heat should be transported mainly by the sample flow and not by thermal conduction within the diaphragm. Therefore the diaphragm has to be as thin as possible making it very fragile.

Experimental

Sample Preparation

The sensor structures (Fig. 1) are evaporated on a <100>-Si wafer, passivated on both sides with 250 nm SiO_2 and 70 nm Si_3N_4. A chromium meander (300 µm x 5 µm x 130 nm, 580 Ω) serves as heater. The thermistors consist of amorphous germanium (250 nm, 75 µm² x 5 µm, 320 kΩ). Amorphous germanium was chosen as thermistor material because its resistivity is highly sensitive to temperature changes [2]. It exhibits a TCR of about -1.8%/K being almost five times higher than the corresponding value of platinum. The thermistors are contacted by an interdigital sandwich structure consisting of 50 nm titanium (at the germanium side), 100 nm gold and 30 nm chromium.

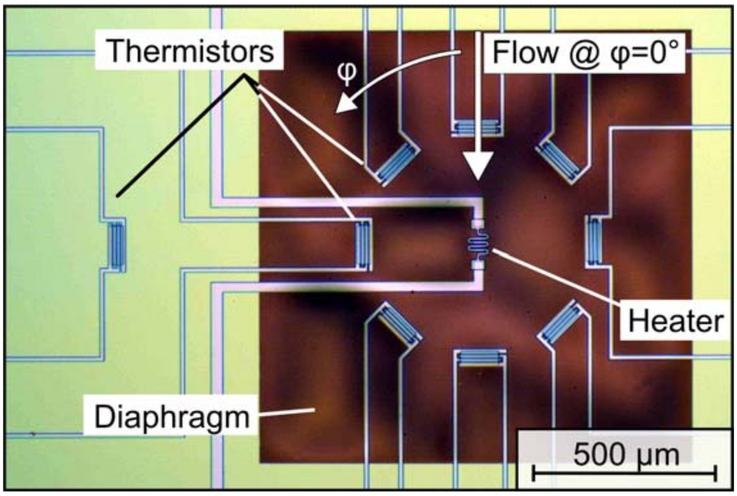

Fig. 1: Micrograph of the flow sensor consisting of eight thermistors on the 1.3 µm thick diaphragm and one on the surrounding Si-frame to measure the ambient temperature. φ denotes the direction of the flow in respect to the N-S-direction. Due to the buckling of the diaphragm it is irregularly shaded.

The metal layer and the Ge layer are evaporated and patterned with an image reversal photo resist. The complete structure is isolated by 1 µm thick LPCVD silicon nitride. Finally, the diaphragm is generated by anisotropic etching with a 30 wt% potassium hydroxide solution at 80 °C. The etching process is stopped by the silicon oxide layer of the wafer. The diaphragm features a size of 1.2 x 1.2 mm^2 and an overall thickness of 1.3 µm. It is an inherent property of the anisotropic etching process of a <100>-Si-wafer that the boundaries of the etched cavity are formed by {111}-planes [3]. Therefore the cavity is a truncated pyramid, bounded by a rectangular silicon nitride membrane.

Measurement Setup

The sensor is positioned flush with the wall of a flow channel (rectangular cross-section of 12 mm x 1 mm) and can be rotated 360° as indicated in Fig. 1. Filtered nitrogen is used as fluid and controlled by a flow controller allowing a maximum velocity of 2.8 m/s. The central Cr resistor is heated up by 430 µW in the constant voltage mode (over-temperature of approximately 5 K). The thermistors resistances are measured by applying constant voltage (5 V) and current-to-voltage converters (120 mV/µA) based on the ultralow noise BiFET OpAmp AD743. Their output voltages are recorded by a PC-controlled data acquisition board (Fig. 2).

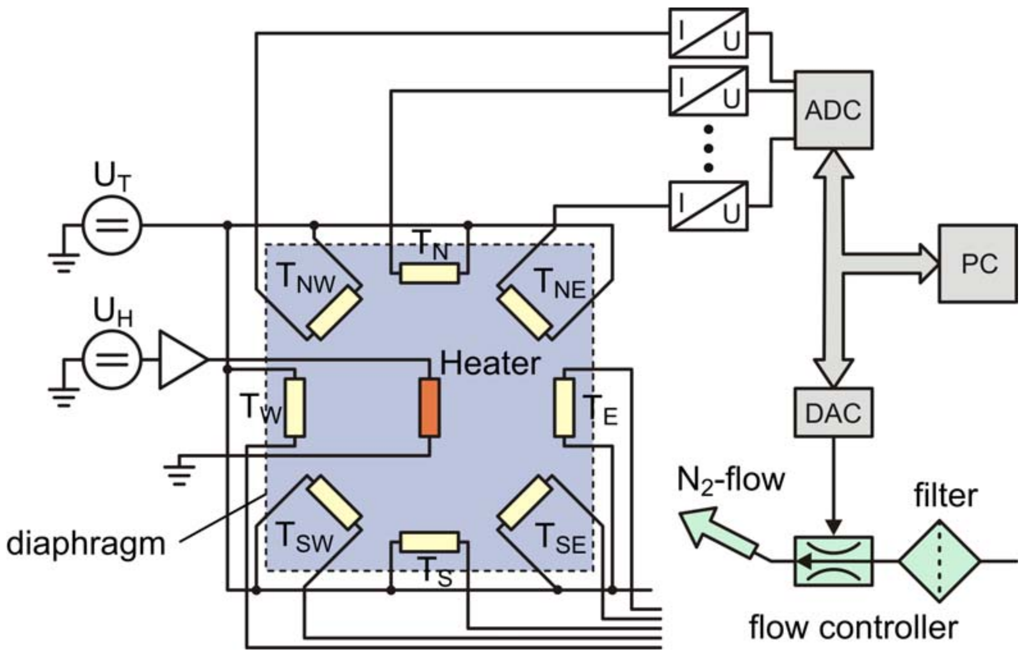

Fig. 2: Schematic measurement setup. Thermistors T_N, T_{NE}, T_E, … T_{NW}, U_T thermistor voltage, U_H heater voltage.

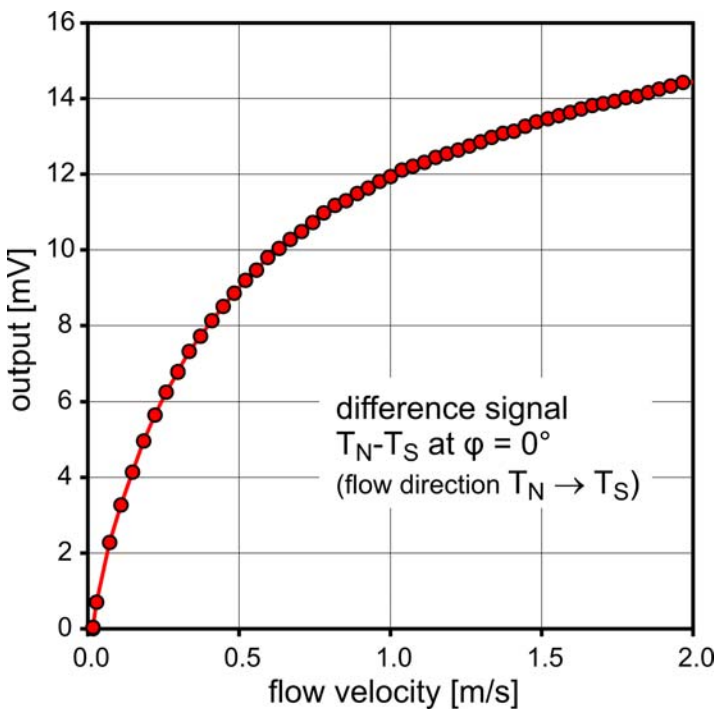

Fig. 3: Difference signal ($T_N - T_S$) of the thermistors at the north and south position versus flow velocity. The channel is oriented in parallel to the connecting line of the thermistors. Heating power: 430 µW.

Measurements

As an example, the measured difference signal of the north/south thermistor pair (Fig. 3) emphases the high sensitivity of the sensor for flow velocities. The gas flows parallel to N-S-direction, the heater is operated in the constant heating power mode. For low velocities the sensitivity is 30 mV/(m/s). At higher velocities the overtemperature of the upstream thermistor vanishes. Also the downstream sensor gets less and less heated because more and more gas has to be heated up. Beyond a velocity of 3 m/s the temperature difference decreases with increasing flow rate.

The dependence of the difference signal of opposed sensors versus flow direction is plotted in Fig. 4 (thick lines). The direction sensitivity for flow with an angle smaller than 60° in respect to the connecting line is about 150 µV/°. Evaluating the signal difference of 90° rotated thermistors (e.g., S-E) the directional sensitivity can be improved by approximately 50%, when the thermistor pair is near the downstream position.

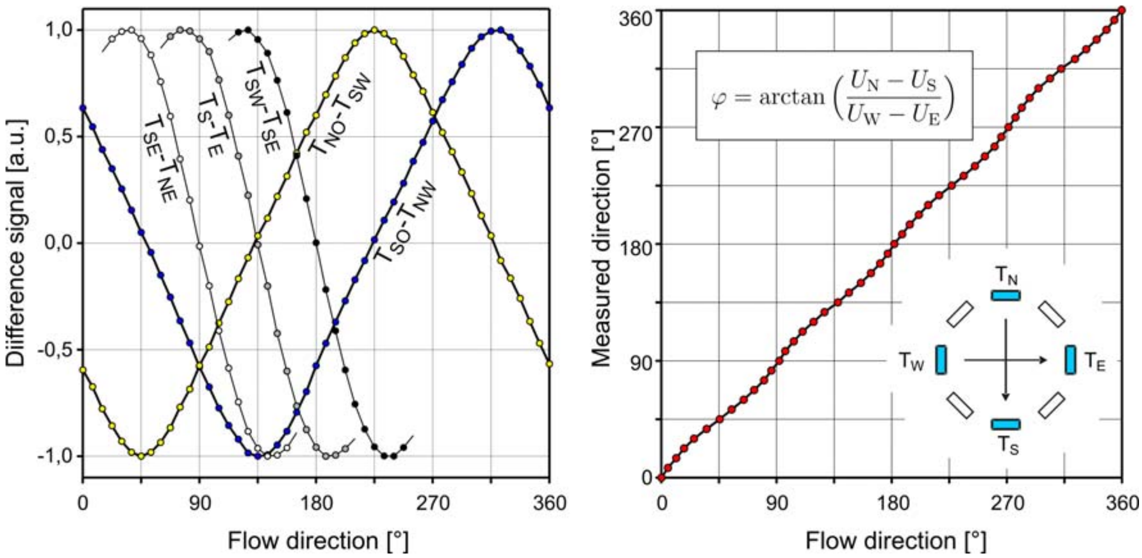

Fig. 4: Left: Measured and normalized difference signals of opposed (thick lines) and of 90°-rotated thermistors (thin lines). Right: Measured flow direction assuming sinusoidal characteristic of the difference signals of opposed sensors (N-S and W-E).

The value of the angle of the flow direction can be determined using the difference signals of two thermistor pairs: $\varphi = \arctan[(U_N - U_S)/(U_W - U_E)]$ taking into account the signs of the individual differences to decide the quadrant. The function assumes a sinusoidal response of the difference signal to the flow direction. The deviations from this are mainly responsible for the nonlinearity in the measured direction of Fig. 4.

Conclusion

The application of amorphous germanium enables the development of highly sensitive sensors for flow velocity and flow direction measurement. By applying eight thermistors the angular resolution can be increased by about 50%. The directional characteristic of a single thermistor deviates significantly from a sinusoidal function. A very high accuracy is achievable using all available thermistor signals and more sophisticated evaluation schemes. Additionally, improved sensor designs are feasible to take full advantage of the superior properties of the thin-film thermistors.

References

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