TOWARDS A GAS INDEPENDENT THERMAL FLOW METER

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ABSTRACT

We present a novel potentially gas-independent thermal flow sensor chip that contains three two-wire calorimetric flow sensors to measure the flow profile and flow direction inside a tube, and a single-wire flow-independent thermal conductivity sensor which detects the type of the gas through a simple DC voltage measurement. All wires have the same dimensions of 2000 µm in length, 5 µm in width and 1.2 µm in thickness. Four different gases Ar, N_2, Ne and He were used for the thermal conductivity measurement and the measured output voltage corresponds very well with a theoretical model.

KEYWORDS

Thermal flow sensor, thermal conductivity, calorimetric sensor, Wheatstone bridge.

INTRODUCTION

Thermal flow sensors are used to measure the flow rate of both gases and liquids. There are three types of thermal flow sensors: anemometric, calorimetric and time-of-flight. All three mentioned thermal flow sensor types are typically composed of a heater and temperature sensors; and follow a similar working principle, i.e., supplying power to the heater to elevate the temperature, and then measuring the change in temperature distribution over the sensor structure as a measure for the flow rate [1].

Thermal flow sensors have a simple working principle and low fabrication cost. However, they are dependent on the type of the flowing medium, more specifically the thermal properties of the gas or liquid. It means calibration of these sensors is required whenever the medium changes. There are different ways to make thermal flow measurements medium-independent. In [2], AC excitation was used to measure the voltage of a sensor close to the heater. They used the fact that by increasing the frequency, the thermal boundary layer will decrease and can be brought down close to the wall. Therefore, due to the non-slip condition on the wall, the thermal exchange between the heater and sensor is independent of the velocity, so the heat transfer is only affected by physical properties of the gas or fluid, and not by the flow. Two physical parameters, thermal conductivity κ and volumetric heat capacity ρc_p, are derived from the phase and amplitude of the third harmonic of the measured AC voltage. The flow rate itself is measured with DC excitation which is dependent on the κ and ρc_p. Therefore, by knowing these properties from the AC measurement, a gas independent flow rate measurement can be achieved. In [3], a thermal flow sensor was used consisting of a heater and a downstream temperature sensor to measure the thermal conductivity of the gas. The temperature of the downstream temperature sensor in a specific flow region is only dependent on κ. Another technique is to measure the thermal conductivity by decreasing the dependency of the wire temperature on flow using different structures or implementing the sensor in a dead volume [4, 5, 6]. However, this technique is only suitable for flow sensors inside micromachined channels. In this paper, a novel design is proposed for a sensor probe that can be used to measure the flow rate in a larger tube. It can simultaneously measure the thermal conductivity by simply using a single heated wire with a DC voltage measurement. Moreover, the chip contains three pairs of flow sensing wires to measure the flow velocity at different locations in the tube.

DESIGN AND FABRICATION

Fig. 1(a) shows a schematic drawing of the sensor chip on a PCB, consisting of three pairs of wires realized at the front and back side of a silicon wafer to form calorimetric flow sensors, see Fig. 1(b), and two single wire structures to form thermal conductivity sensors, see Fig. 1(c). The distance between the wires in the flow sensor is 380 µm, which is defined by the wafer thickness. Fig. 2(a) shows the circuit schematic of the Wheatstone bridge. Resistors R_1 and R_4 are fixed resistors integrated on the silicon chip. Resistors R_2 and R_3 are the sensor wires. In no-flow condition, R_1 and R_4, and R_2 and R_3 have the same value, so the output signal of the Wheatstone bridge V_b is zero. When flow is applied, the heat will be transferred from the upstream wire to the downstream one. Therefore, there will be a positive or negative (depending on the flow direction) output voltage signal as a result of the temperature difference between the two wires R_2 and R_3.

An additional wire is suspended above a shallow V-groove cavity for thermal conductivity measurement. Fig. 2(b) shows a schematic cross-sectional drawing of V-groove with under etched beam. The V-groove cavity has a length of 2000 µm and a width of 40 µm. The temperature of this wire is dominated by the thermal conductivity of the gas inside the cavity and largely independent of the flow velocity. Hence, by monitoring the voltage drop over the wire at constant heating current, κ can be detected. Fig. 2(c) shows the circuit schematic of the thermal conductivity sensor.

Fig. 3 shows a summary of the fabrication process and photograph of the released chip. Because of the large aspect ratio of the beam length to the channel width, a good alignment to the crystal orientation {111} is required to minimize the under etch. Therefore, a Vangbo mask is used to obtain the required crystal orientation [7]. A layer of 150 nm LPCVD deposited SiRN is used as the etch mask to transfer the Vangbo pattern. By wet anisotropic etching in KOH (25 wt.% – 75 °C – etch time 10-15 minutes), the crystallographic orientation of a silicon wafer can be found easily and within an error of ± 0.05 degrees. Fig. 3(a) shows the Vangbo mask and the etch structure of the silicon. The second structure shows a perfect alignment while the right structure is not aligned parallel to the {111} crystal orientation, resulting in the unsymmetric under etch.

Fig. 3(b) shows the fabrication process. First, a layer of 1 μm SiRN is deposited by LPCVD (1). Then, a 20 nm Cr adhesion layer and 200 nm Pt layer are deposited and etched by sputtering and IBE etching, respectively, to pattern the wires and metal traces (2, 3). The IBE etching step is performed twice with two different masks. The first step is for transferring the metal pattern, the second one to narrow the beam width and define the pattern in the SiRN layer. In (4), SiRN is etched by plasma etching to open the window for etching the Si. All these steps are repeated for the backside of the wafer to have wires on both sides (5-7). Finally, Si is etched by KOH (KOH 1:3 DI-water) to realize a cavity inside the wafer between the two wires (8).

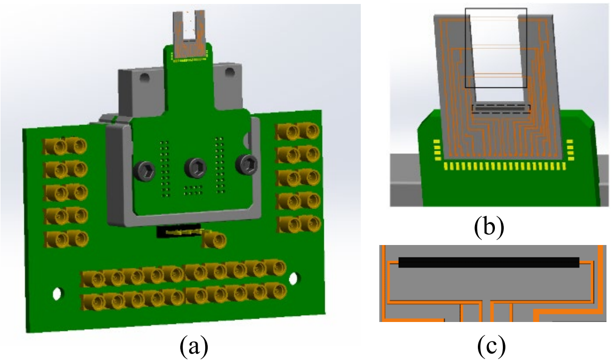


Figure 1: (a) Schematic drawing of the sensor on PCB, (b) chip (solid line and dashed line show the thermal flow sensors and thermal conductivity sensor, respectively), (c) a close-up image of thermal conductivity sensor with the cavity underneath. All wires are 2 mm long, 5 μm wide and 1.2 μm thick.

RESULTS AND DISCUSSION

Fig. 4 shows the experimental setup, consisting of a flow controller, pressure controller, digital voltmeter, and a 3D printed tube with the chip inside it. Each of the three wire pairs that are used as thermal flow sensor forms half of a Wheatstone bridge. The other half of the bridge is formed by fixed on-chip resistors. The sensor wires are heated by the power supply of the bridge, which is 2 V. A difference in temperature between the wires will result in an output voltage. At room temperature all wires have a resistance of approximately 300 Ω. Fig. 5(a) shows the measured output voltages of the three sensors as a function of volumetric flow rate of N_2. The sensitivity clearly depends on the location of the sensor wires, showing that the device can be used for measuring the flow profile. As can be seen, the upper wire is more sensitive to the flow in comparison to the other pairs. He and Ar are also used for thermal flow measurement, see Fig. 5(b). It shows that the voltage of the Wheatstone bridge is dependent on the type of the gas.

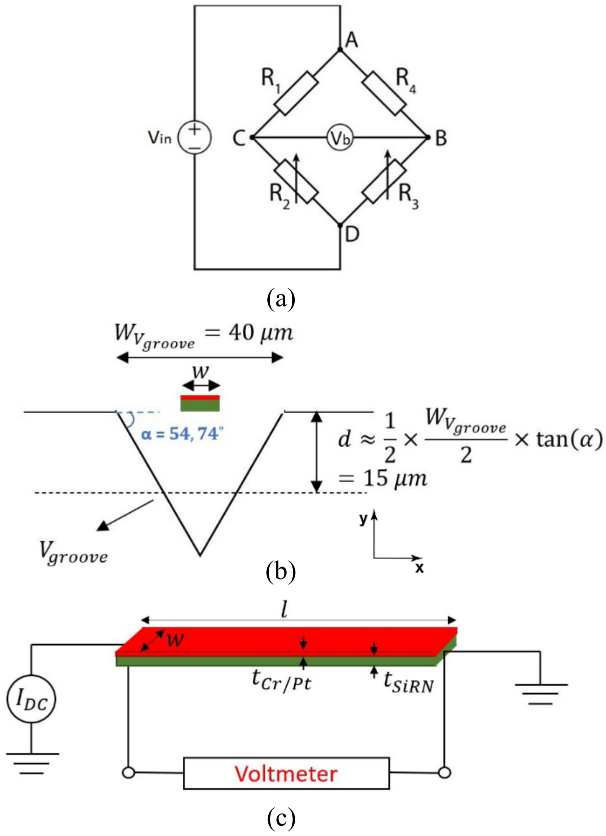


Figure 2: (a) Circuit schematic of the Wheatstone bridge (The bridge is fed by 2 V). (b) Schematic cross-sectional drawing of V-groove with under etched beam. (c) Circuit schematic of the thermal conductivity sensor. A 5 mA DC current is applied to the wire, and voltage of the wire is measured with a digital multimeter.

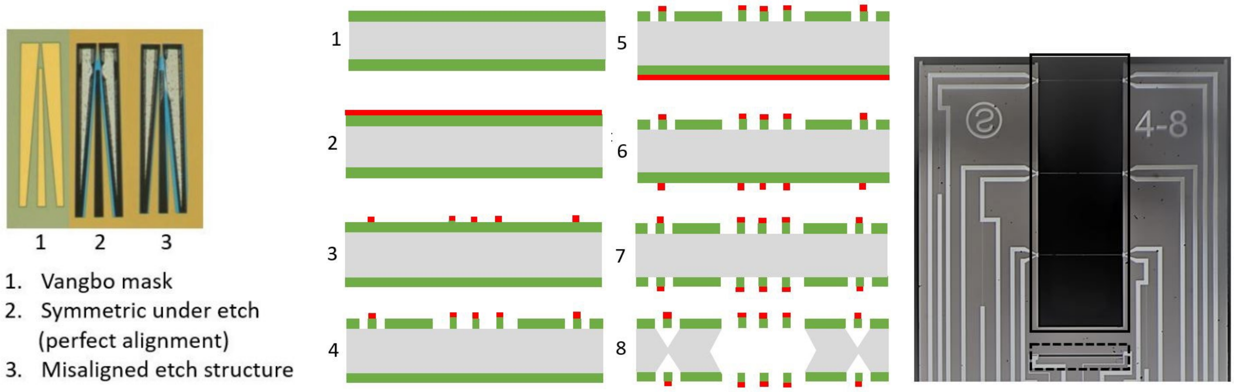
Next, the wire suspended above the V-groove cavity was used to measure the thermal conductivity of the gas simultaneously. The temperature profile $T(x)$ along the length of the beam can be expressed as [5]:

$$\frac{\Delta T(x_n)}{P'} = \frac{1}{G'_f}\left(1 - \sqrt{\frac{\cosh\left(x_n l\sqrt{R'_b G'_f}\right)}{\cosh\left(\frac{1}{2} l\sqrt{R'_b G'_f}\right)}}\right) \quad (1)$$

$$G'_f = k\frac{w}{d} \quad (2)$$

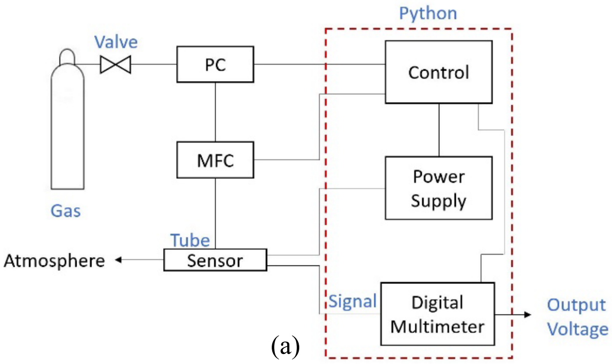
$$R'_b = \frac{1}{kA} \quad (3)$$

In the equations x_n is the dimensionless normalized position along the wire, l is the length of the wire, w and d are the width and depth of the cavity, and A is the cross-sectional area of the beam. P' is the electrical line power in [W/m] dissipated at position x_n, G'_f is the line conductance through the gas in [W/(Km)], and R'_b is the thermal line resistance of the beam in [K/Wm]. When the temperature is known, the voltage over the wire can be easily calculated ($V = R_a(1 + \alpha\Delta T) \times I$). Fig. 6(a) shows the calculated temperature distribution along the normalized wire length. Fig. 6(b) shows the measured voltage drop over the thermal conductivity sensor at 5mA heating current as a function of flow for He, Ne, N_2 and Ar. The measured voltage depends strongly on the thermal conductivity of the gas. At low flow levels we

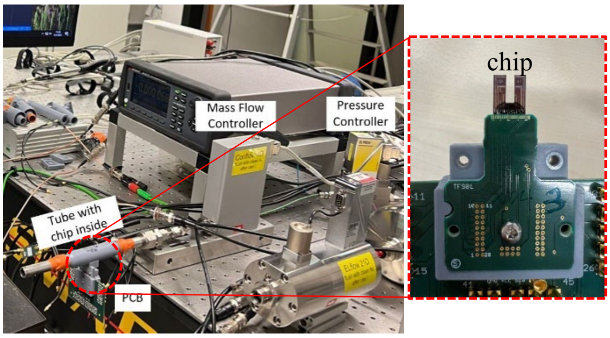


(a) (b) (c)

Figure 3: (a) Vangbo mask and the etch structure of the silicon. (b) Overview of the fabrication steps. Microscope photograph of the released (b) thermal flow and (c) thermal conductivity sensor. (1) LPCVD of 1 μm SiRN, (2) sputter a layer of Cr/Pt (20 nm/200 nm), (3) IBE etching of Cr/Pt, (4) SiRN layer is etched by plasma etching to open the window for etching the Si. (5-7) All these steps are repeated for the backside of the wafer, (8) Finally, Si is etched by KOH (KOH 1:3 DI-water) to realize a V-groove and a cavity inside the wafer between the wires. (c) Microscope photograph of the released sensor (solid-line: thermal flow sensor and dashed-line: thermal conductivity sensor).



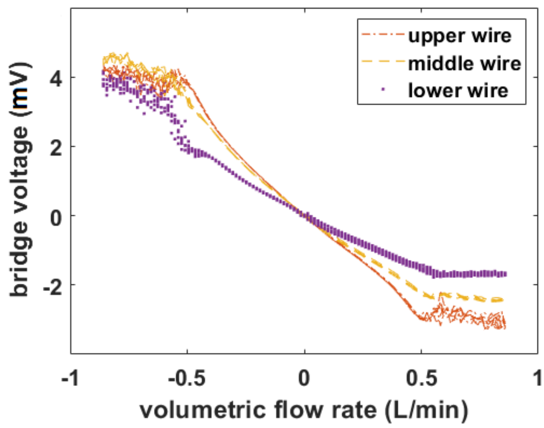
(a)



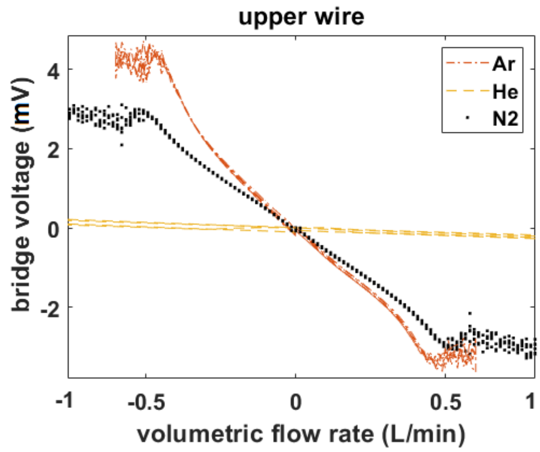
(b)

Figure 4: (a) Schematic drawing of the measurement setup. (b) Experimental setup. The setup consists of a pressure and flow controller for providing the gas flow to the 3D printed flow tube, excitation system for heating the wire, and data acquisition system for reading the voltage of the wire. Acquisition is implemented in a Python program. Red dashed line shows the PCB with the chip mounted on it.

see an influence of the flow because of outside air entering the tube. Fig. 7 shows the measured voltage as a function of thermal conductivity together with a theoretical curve that was calculated using the equation (1). The measured voltages correspond very well with the



(a)



(b)

Figure 5: (a) Measured Wheatstone bridge voltage as a function of volumetric flow rate (L/min) for three pairs of wires with N_2. (b) Bridge voltage of upper sensor versus volumetric flow rate for three gases (N_2, He and Ar).

theoretical response. The output signal of the flow sensor can be adjusted with the measured thermal conductivity to be able to measure the flow rate independent of the gas type.

CONCLUSION

In this paper a novel potentially gas-independent thermal flow sensor chip is presented. It consists of three pairs of wires used as calorimetric flow sensors to measure the flow profile and flow direction inside a flow channel, and a flow-independent thermal conductivity sensor which detects the type of gas through a simple DC voltages measurement. Four gases, Ar, N_2, Ne and He were used for the thermal conductivity measurement and the measured output voltage corresponds very well with the theoretical model. The results show that the proposed thermal flow sensor is potentially capable of measuring the flow rate independent of the type of gas. Next steps will include the adjustment of the output signal of the flow sensor for the actually measured thermal conductivity to demonstrate the capability of the flow sensor to measure the flow independent of the gas type.

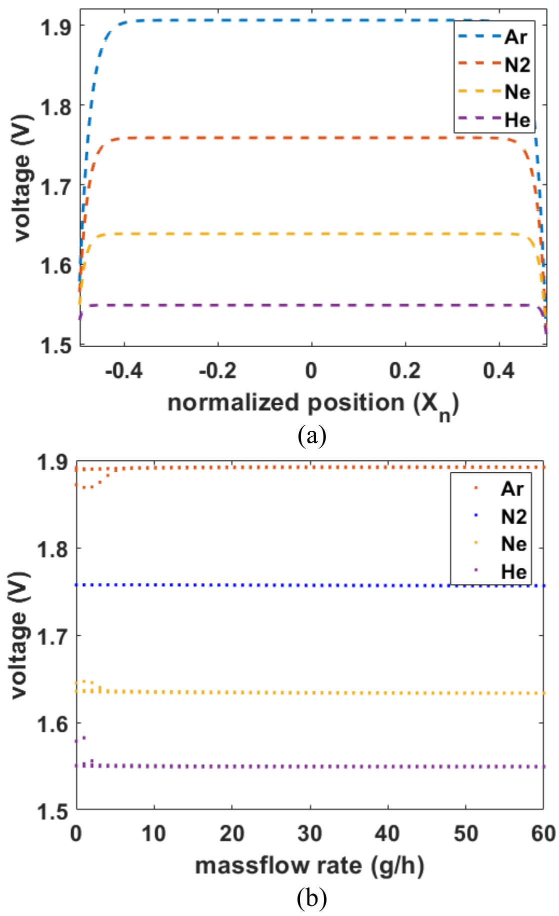


Figure 6: (a) Calculated temperature distribution along the beam of the thermal conductivity sensor for four different gases (He, N_2, Ne, and Ar). (b) Output voltage of the thermal conductivity sensor versus mass flow rate for He, N_2, Ne, and Ar. The wire is heated with a constant current value of 5mA, and the voltage of the wire is measured.

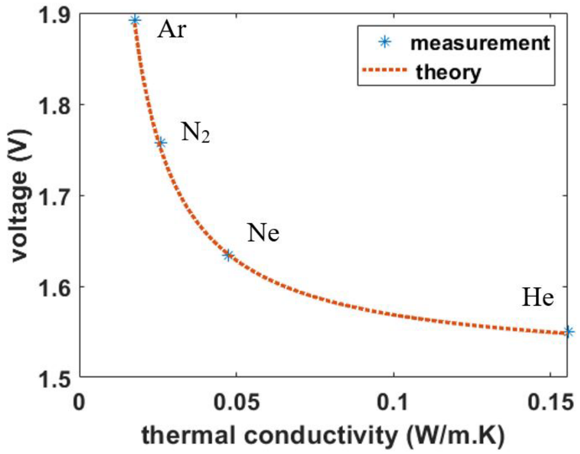


Figure 7: Theory and measurement results comparison. The dashed graph is derived from the stationary temperature distribution equation (1).

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