

MICROMACHINED SEMICONDUCTOR FLOW SENSOR

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Abstract: Miniaturized flow sensors based on thin film germanium thermistors offer high flow sensitivities and short response times. The thermistors are placed on a silicon nitride diaphragm carried by a silicon frame. Using the controlled overtemperature scheme the measurable airflow velocity ranges from 0.001 m/s to 200 m/s. The response time to large step changes of the air velocity is less than 20 ms. Our experiments show that the sensor is also applicable to acoustic flow measurements.

Keywords: Electrocalorimetric flow measurement, thin film germanium thermistors, micromachined flow sensor.

1 INTRODUCTION

There is a growing demand of micro-flow sensors for industrial, automotive, domestic and medical applications. The measuring principle can be based on thermistors, thermopiles, pyroelectric elements, pn-junctions, resonating microbridges, Prandtl tubes and several other effects [1-10]. Micromachining is adopted to achieve high sensitivity, quick response and low power consumption.

The electrocalorimetric flow sensor presented here is based on a heat transfer principle in which a heated body is cooled by a passing flow and the local rate of cooling depends on the flow velocity [11]. One important application of flow sensors is the measuring of the instantaneous air intake of combustion engines. Knowledge of this combustion process parameter is essential if one tries to minimize both the engines fuel consumption and the pollution of the environment. For the development of such engines a wide velocity measuring range and high resolution monitoring of the time course of the air velocity is desirable.

2 SENSOR CONSTRUCTION AND TECHNOLOGY

A (100) silicon wafer has been used for the fabrication of the sensor. The chip size is 2 mm x 4 mm and the thickness is 0.3 mm. Two thin film thermistors are placed symmetrically to a central heater on an 800 nm thick silicon nitride diaphragm (Fig.1a). Additional thermistors are arranged at the rim of the silicon chip. These so called substrate thermistors are used to measure the fluid temperature, which is close to the substrate temperature.

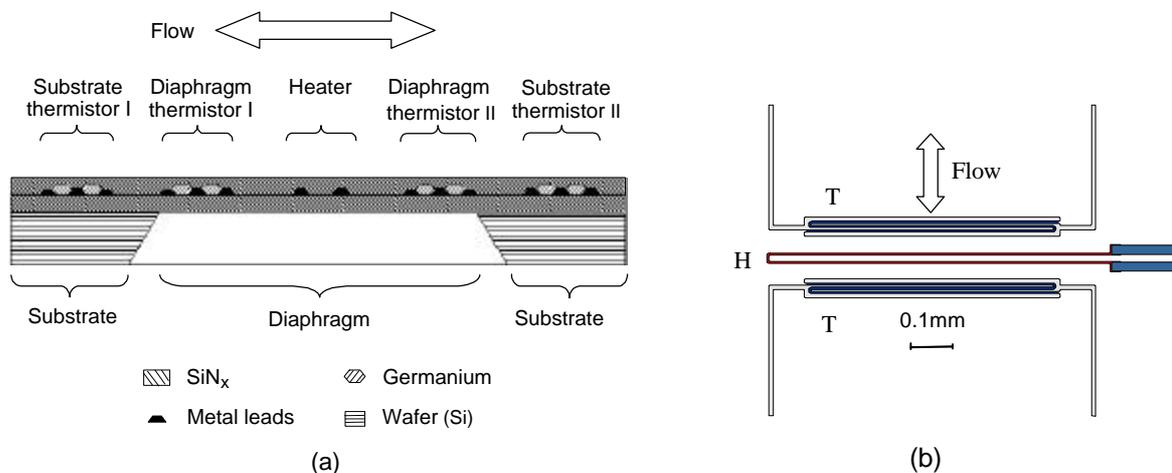


Fig.1: (a) Schematic cross section of the sensor. The size of the diaphragm is 0.5 mm x 1.1 mm.
(b) Top view of the thin film structures on the sensor diaphragm. H, heater; T, thermistors.

All thermistors are fabricated by evaporation of amorphous germanium onto comb-shaped electrodes (Fig.1b). One advantage of using this type of high temperature-resolution thermistors is that reliable flow sensing operation requires only a small temperature difference between the heater and the fluid. The presented sensor operates with heater overtemperatures less than 25 K. Full resolution is already obtained with a heater overtemperature of 10 K. The increase of the fluid temperature caused by the heater is much smaller than these overtemperatures. So the sensor is especially applicable in such cases where the heater must not cause a significant increase of the fluid temperature.

The maximum electrical power rating of the heater is 40 mW if the fluid is air. However, the typical operating power is about 4 mW, which corresponds to a heater voltage of 3 V. Both platinum and nichrome have been applied as the heater material.

The thin film structures were produced on a wafer, which has been covered by a silicon nitride layer. Finally, a low stress silicon nitride protective film is deposited nearly at room temperature using a PECVD process. The low deposition temperature prevents the germanium film from recrystallization. Both silicon nitride layers are forming the diaphragm of the micromachined sensor. Silicon nitride exhibits a low thermal conductivity resulting in high flow sensitivity. The thermal conductivity of silicon nitride is about 2.3 W/m·K as compared to 150 W/m·K for silicon. A further advantage of the silicon nitride diaphragm is its small thickness resulting in a small thermal conduction. However, it should be mentioned that a low thermal conductance of the diaphragm has some negative influence on the dynamic behavior of the sensor. The 800 nm thick diaphragm used in our sensor has been proved to be very stable in a tangential flow (Fig.1a).

Amorphous germanium exhibits high values of both the resistivity and its temperature coefficient. The temperature coefficient of resistance is approximately -2 %/K and the resistivity is about 5 Ωm at room temperature. A layout as shown in Fig.1b and a 250 nm thick germanium film result in a resistance of 70 kΩ at 20 °C. The measured resistance versus temperature characteristic of the thermistor is shown in Fig. 2a. It has been proved that the long-term stability of this characteristic is better than 0.5 % per year. A noise equivalent temperature difference of 10 μK for a bandwidth of 10 Hz is achieved with this thermistor technology [10]. For comparison, Johnson noise only would limit the resolution to 4.75 μK.

For calibration in a wind tunnel and other experimental measurements the sensor chip is glued to a 0.15 mm thick printed circuit board (PCB) flush fitted with the board surface (Fig.2b). For this purpose the flexible PCB was formed using an embossing die. The dimension of this PCB in the direction of flow is 60 mm and the sensor was placed midway. The ground plane of the PCB shields the signal leads against interferences.

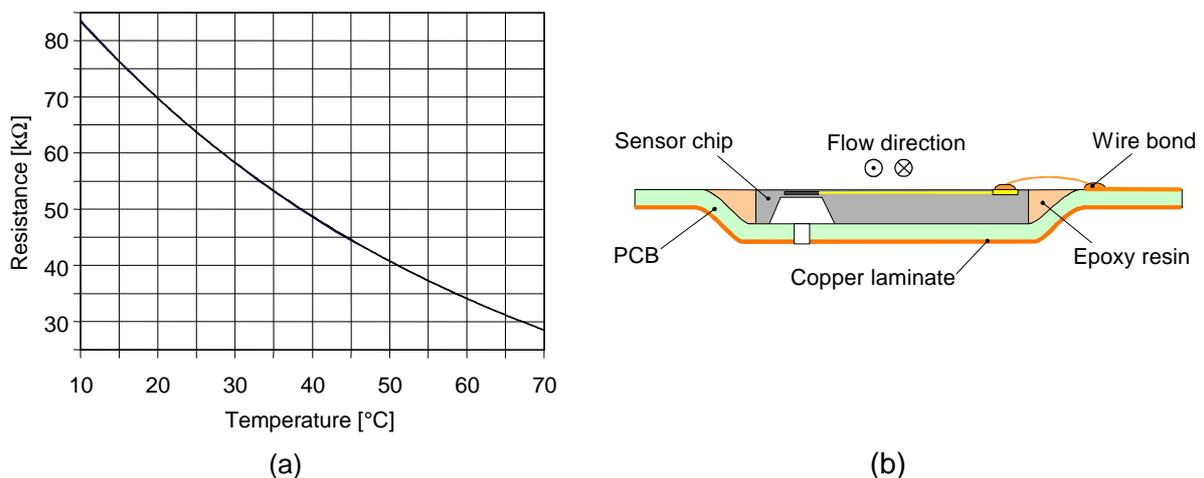


Fig.2: (a) Measured temperature dependence of the resistance of thin film germanium thermistors, (b) Schematic cross sectional view of the sensor mounted on a flexible printed circuit board.

3 ELECTRONIC SET-UP

Operating the miniaturized flow sensors with constant heating power usually result in a very limited flow measuring range. Because of efficient convective cooling at very high flow rates the overtemperatures of the heater and the diaphragm thermistors as well as the sensor output signal decrease with increasing flow. Thus the sensor signal is not a monotonous function of the flow if this operating

mode is used. In order to obtain a wide measuring range a constant temperature difference between the diaphragm and the fluid is desirable and an electronic controller is needed to ensure this operating mode. However, this temperature controller has to be disabled in the case of investigations of the dynamic properties of the sensor. Then the sensor is operated in the constant power mode.

A block diagram of the used electronic set-up is shown in Fig.3. For small temperature changes the electrical conductivity of the thermistor varies approximately linear with temperature. Thus temperature signals were derived from each thermistor conductance. Furthermore the conductance values of the four thermistors are transformed into voltage signals by a signal-conditioning unit. An electronic PI-controller is used to establish a constant difference between the temperature mean of the two diaphragm thermistors and the temperature mean of the two substrate thermistors [11]. This corresponds closely to a constant overtemperature condition of the heater with respect to the fluid temperature over the whole flow range. The dynamic behavior of the controlled system, which is determined by the thermal properties of the sensor diaphragm, restricts the dynamic behavior of the presented temperature-tracking controller. These thermal properties can be characterized by a temperature transportation time and a thermal delay time; both of them can easily be estimated by observing the diaphragm thermistor response caused by voltage steps applied to the heater.

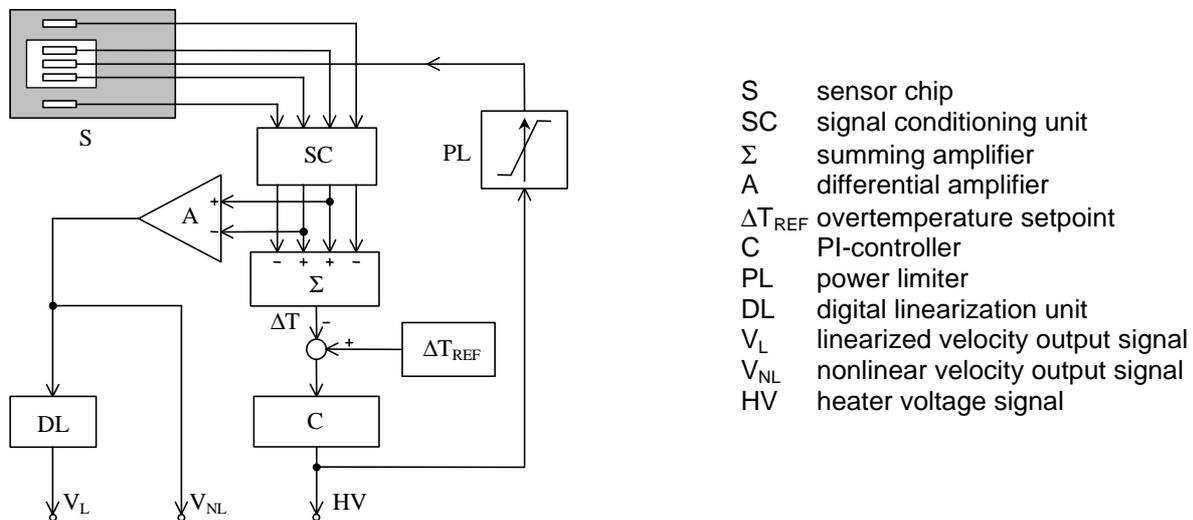


Fig.3: Block diagram of the electronic circuit.

The temperature difference between the two diaphragm thermistors, used for the generation of the output signal, is a nonlinear measure for the flow velocity of the medium (Fig.4a). An output signal proportional to the flow velocity value is accomplished within 25 μ s by digitizing the raw signal and performing a special lookup table transformation followed by a digital to analog conversion. This linearization method can also be used for example to compensate for an asymmetry of the sensor structure and to calibrate the sensor for different flow geometry. The chosen resolution for digitizing the sensor signal was 12 bit. Performing the lookup table transformation the digital raw value is interpreted as the 12 bit address pointing to the read only memory location, which contains the digital equivalent of the linearized value. Therefore a monotonous sensor characteristic is a necessary precondition for the applicability of this linearization method. A great advantage of this linearization is that any digitized information about further interfering physical parameters like the ambient temperature or humidity can be put into lookup tables with an address space of more than 12 bit width. These wider tables have to contain a set of sensor characteristics according to ambient temperature or humidity variations.

4 MEASUREMENTS AND RESULTS

To obtain the free field calibration curve shown in Fig.4a the PCB carrying the sensor was placed along the direction of flow in a wind tunnel. The PCB design ensures a defined boundary layer over the whole stationary flow range.

To estimate the achievable measuring range for flow rates a sensor was mounted flush with the wall of a 10 mm long rectangular flow channel. Low flow rates were established by syringe pumps whereas a standard mass flow controller was used in the high flow rate regime. Fig.4b demonstrates the extraordinary wide flow measuring capability of the sensor, which spans more than five orders of magnitude. For flow channel dimensions of 0.45 mm height and 1.2 mm width a measuring range from

0.6 cm³/h to at least 150 000 cm³/h was observed. This range corresponds to average flow velocities from 0.31 mm/s up to 75 m/s. In Fig.4b the two monotonous increasing characteristics belong to the constant overtemperature mode using 23 K and 10 K overtemperature. The third characteristic, which corresponds to an operation at a constant power of 4 mW, shows a decreasing sensor signal at high flow rates. The use of the constant overtemperature scheme extends the flow rate measuring range by more than two orders of magnitude compared to the constant power scheme.

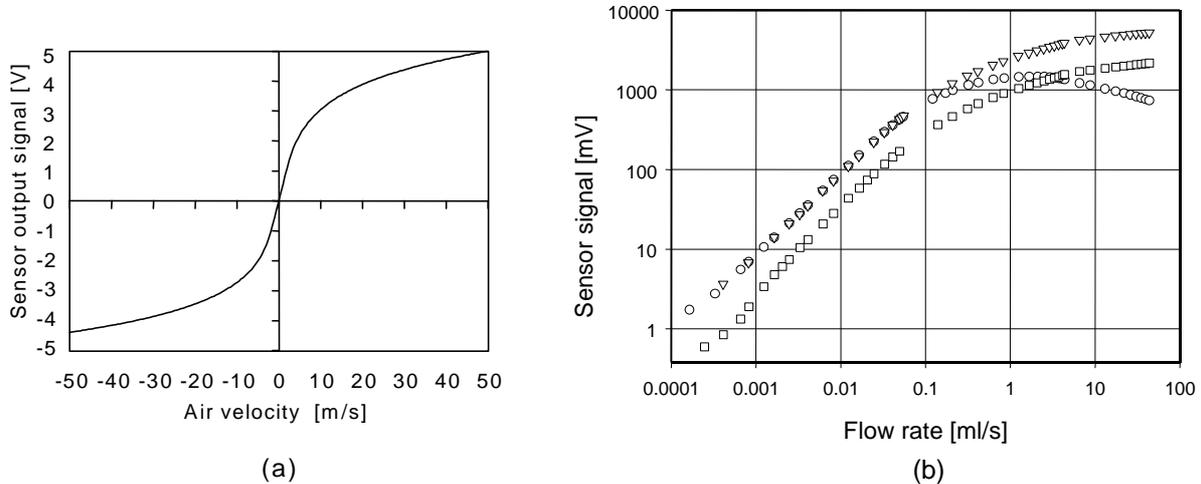


Fig.4: (a) Output signal prior to the linearization of the sensor signal as a function of the air velocity (calibration curve). The asymmetry of the curve is caused by a mask-misalignment during sensor fabrication. (b) Sensor signal versus flow rate for the constant overtemperature mode (23 K (J), 10 K (I)) and the constant power mode (I).

Figure 4b shows that the sensor signal varies by a factor of $5 \cdot 10^3$ whereas the flow rate varies over five orders of magnitude for this setup. Thus the nonlinear sensor characteristic compresses the dynamic range by two orders of magnitude, which can be considered as an advantage if the signal has to be converted into digital information. A 1% resolution of the flow measurement can be achieved within a flow measuring range from ± 0.3 ml/s to ± 30 ml/s after a 12 bit analog to digital conversion of the sensor signal. This is twice the measuring range that can be expected for a sensor with a linear characteristic. For a 16 bit quantification a flow measurement resolution of better than one percent can be maintained from ± 0.02 ml/s to ± 40 ml/s, corresponding to a threefold better dynamic range compared to a linear sensor.

The dynamic properties of the sensor were investigated by step changes of the air velocity, shock waves and acoustic air oscillations. For these studies the sensor was mounted on a PCB and placed at the center of a 1 m long acrylic glass tube of 50 mm diameter. Airflows were generated with a speed-controlled exhauster enabling mean air velocities up to 200 m/s. Step changes of the air velocity were produced, e.g. by abruptly blocking the tube inlet. Alternatively, shock waves have been generated by blasting balloons in a 0.25 m long vessel mounted at one end of the tube.

Due to the sensor layout (Fig.1) and the small thickness of the diaphragm these sensors respond very quickly to step changes of the air velocity. In the constant overtemperature mode the sensors show a response time of less than 20 ms to large step changes of the air velocity depending on both the size and the direction of the step.

Our experiments show that the sensor is also applicable to acoustic flow measurements. We have detected sound frequencies up to 13 kHz in the constant power mode. The properties of this acoustic flow sensor are comparable to the so called μ -flown [4]. This expression indicates the applicability of the flow sensor to a microphone. However, it should be mentioned that a usual microphone works on the principle of a pressure sensor.

A Bode-plot of the sensor signal for small acoustic flows is depicted in Fig.5a. The sensor was operated in the constant power mode. Acoustic flows at various frequencies were generated by a sinusoidal driven loudspeaker and the sound pressure level was kept constant using the response of a reference microphone. This figure is of qualitative nature only because no calibrated sound equipment was available. In response to acoustic flows a -40 dB/decade slope was observed with a corner frequency of 1 kHz (Fig.5a), which is in reasonable agreement with the rise time data. The slope in the diagram can be attributed to two mechanisms. Firstly there is a delay by the thermal mass and the thermal conductivity of the diaphragm and secondly there is a decrease of convective heat transport

with increasing frequency. For constant sinusoidal acoustic flow the amplitude of the air movement is inverse proportional to the frequency of the oscillation [12] and thus the convective heat transport decreases with increasing frequency.

The signals shown in Fig.5b were recorded using the constant overtemperature mode with the PCB carrying the sensor located in the 50 mm acrylic glass tube. The lower trace shows the response of the sensor to a shock wave generated by a bursting balloon. The shock wave efficiently stimulates acoustic oscillations corresponding to different resonance frequencies of the one-sided closed volume consisting of the tube and the balloon vessel having a total length of 1.25 m. The oscillation frequency that is predominant in the sensor signal of Fig.5b corresponds to a wavelength close to 1 m, which is approximately 4/5 of the total length. At this resonant frequency the acoustic flow is enhanced according to the position of the sensor, which was placed at 0.5 m or half a wavelength from the open end of the tube. At this position the acoustic flow of the standing sound wave has a minimum. In the upper part of Fig.5b the course of the controller output is plotted. As can be seen the convective heat transfer is related to the oscillation amplitude of the sensor signal. But the heater voltage trace does not follow the acoustic oscillations indicating that the temperature average of both diaphragm thermistors oscillates much less than their temperature difference. It can be concluded from the sensor signal shown in Fig.5b that mainly acoustic resonance oscillations were excited by the shock wave due to the flow channel dimensions of this arrangement.

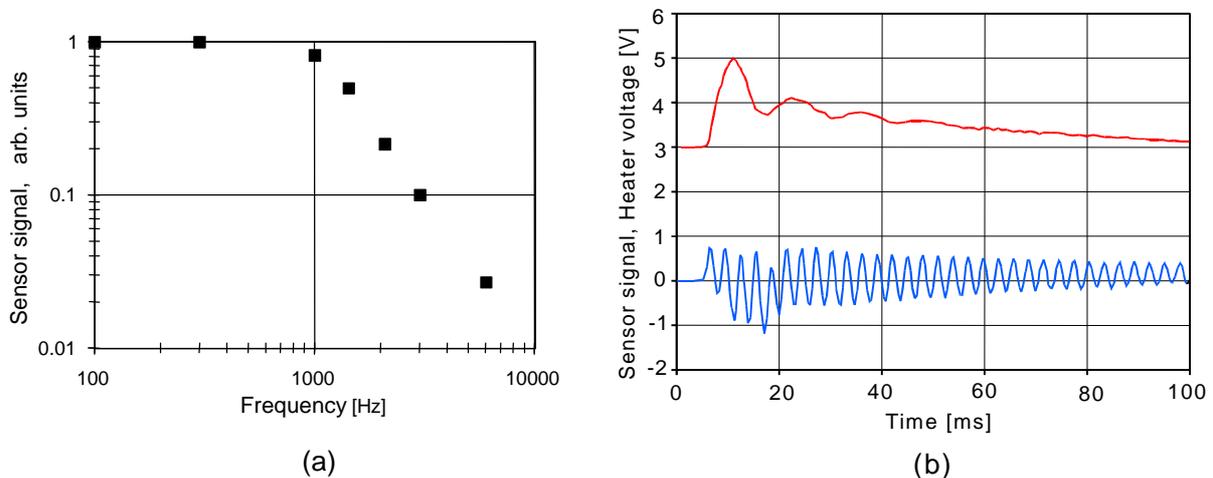


Fig.5: (a) Bode-plot of the acoustic flow signal of the sensor, (b) Sensor- and heater voltage in response to a shock wave in a cylindrical tube. The oscillation frequency of 340 Hz corresponds to a wavelength of nearly 1 m whereas the length of the one-sided closed tube measures approximately 1.25 m.

5 CONCLUSIONS

The extraordinary high temperature resolution of typically better than 10^{-4} K offered by amorphous germanium [1] as well as the excellent matching of thermistor resistances result in a high flow sensitivity. Miniaturized flow sensors based on germanium thermistors are fast responding and can span at least four orders of magnitude of the flow velocity if they are operated in the constant overtemperature mode. Due to the high temperature sensitivity of the thermistors an overtemperature of only a few K is sufficient for an extreme wide measuring range.

We have developed a sensor, which is capable of measuring air velocities ranging from 0.01 m/s to about 200 m/s in a flow tube of 50 mm diameter. With very small channels we have detected air velocities down to 0.001 m/s. With proper flow channel arrangements a measurable range of flow rates spanning more than five orders of magnitude can be achieved.

A simple method for the generation of fast transients of the flow velocity was established which yields flow steps in the millisecond regime. Shock waves can be used in conjunction with proper flow channels as a convenient way to study the transient behavior of miniaturized flow sensors. The rise time of the sensor signal in response to flow steps can be well below 2 ms.

Our experiments show that the sensor is also applicable to acoustic flow measurements. We have detected sound frequencies up to 13 kHz. In response to acoustic flows a -40 dB/decade slope was observed with a corner frequency of 1 kHz. The properties of this acoustic flow sensor are comparable to the so called μ -flown [4].

Besides its high speed the newly developed linearization method offers a flexible way to calibrate the sensor output signal for the quantity to be measured or for a specific flow channel geometry. By this way it is also possible to compensate for a small asymmetry of a sensor and fluid temperature variations.

The wide measuring range of the sensor calls for a linearization circuitry having a resolution of at least 14 bit plus sign. Alternative control circuits may be necessary for special applications [13]. Solutions based on digital controllers will be considered in our future work. Furthermore, we try to achieve shorter response times by an advanced sensor design.

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