Thermal MEMS flow meter for gaseous working fluids on the basis of the hot-wire thermoanemometric sensor

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Abstract. This paper describes the main principles of constructing innovative MEMS flow meters for gaseous working fluids. MEMS flow meter contains hot-wire thermoanemometric sensor which response to the temperature change caused by convective working fluid heat transfer from a hot-wire. The advantages of using hot-wire thermoanemometric sensors were analyzed. The main emphasis of this work is on speed, construction simplicity and small size of the sensor. The new approach to the solution of a problem of sensor output signal relation with the working fluid temperature is presented. This approach is based on adding an extra temperature sensor and a special scheme for thermal compensation to the hot-wire sensor. The temperature scale between temperature sensors (thermistors) corresponds to the flow speed and the flow rate.

1. MEMS flow meters for gaseous working fluids analysis
The problem of precise gas flow calculation is important not only for modern industry but also for many people every day. The most well-known mechanical flow meters [1, 2] are turbine and paddle-wheel meters. These flow meters need additional components when they are used in innovative embedded systems, such as “smart house”. The disadvantages of mechanical flow meters are small lifetime caused by mechanical parts runout and sticking of fluid impurities to the sensor which leads to the corruption of measurement results. Moving parts of mechanical flow meters obstruct the gaseous or liquid flow creating an extra aerodynamic resistance which enlarges the measurement error.

Nowadays we can see an increasing need of modern sensors and transducers in all areas of human endeavour. The technology of silicon sensors constructing can be a solution of a problem of sensor integration into the digital signal processing system. The tendency of using silicon technology for precise sensors is also in modern digital flow meters design. The most common method for gas flow measuring [3-6] is a thermoanemometric method. This method uses convective working fluid heat transfer from hot-wire. The heat transfer is a function of gaseous working fluid speed. The advantages of the thermoanemometric sensor are high sensitivity, high speed, and construction simplicity. The use of silicon technology makes it possible to make the sensor so small that it does not affect the working fluid flow. Now let’s see some innovative, constructive solutions which are used to create thermal MEMS flow meter for gaseous working fluids.

2. Constructive solutions for MEMS flow meter for gaseous working fluids creation
The main problem which occurs while gas flow is measuring with the thermoanemometric sensor is output signal relation with the working fluid temperature. Adding an extra temperature sensor and a
special scheme for thermal compensation to the hot-wire thermoanemometric sensor should solve this problem [5].

In the proposed scheme temperature impact is compensated directly on silicon crystal by adding special thermistor into the Wheatstone bridge measuring electrical circuit. The additional thermistor should be placed along the gas flow directly in front of the heater. This opens up an opportunity to precisely control the heater supply voltage. Comparing the output signal with the plot shows the relation between the heater supply voltage and the thermistor temperature, which was measured while scheme testing on the test bench with a proper digital signal processing [6-8]. This allows us to detect the flow temperature change before touching the crystal and after the flow goes over the heater by measuring two thermistors resistance change. The bigger the difference between the first and the second thermistors temperature is, the higher is the flow speed and the flow rate.

Forming the measuring sensor directly on the silicon crystal provides us with higher flow meter sensitivity. However, some problems connected with crystal material characteristics occur (fig. 1). The first problem is silicon high thermal conductivity. If the heater is placed directly on the substrate, the most part of the thermal energy will expend on heating the substrate. In this case, thermistors would be heated from the silicone substrate to the temperature almost equal to the heater temperature. As a result, the temperature split between two thermistors while measuring the flow rate would be too small to get a stable output signal from the Wheatstone bridge. The second problem is silicon high sensitivity to stresses which occur while forming a conductive structure on the water surface or while placing the crystal into the flow meter body.

Figure 1. Flow meter sensor construction.

The proposed flow meter construction is shown in figure 1. The substrate is made of single-crystal silicon. As a solution to the problem of silicon high thermal conductivity, a 3×3 mm membrane is etched at the central part of the substrate. The thickness of the membrane is 30 μm. There is also a 1×3 mm bridge etched in the center of the membrane.

A “thick” layer of SiO₂ is formed on the silicone substrate for additional heat insulation. The thickness of an insulation layer could be up to 1 mm. The measuring Wheatstone bridge scheme is formed directly on SiO₂ layer.

The problem of stresses which affect flow meter sensor output signal is multidimensional and should be solved at every stage of flow meter design. Silicon crystal is attached to the substrate made of Pyrex borosilicate glass with electrostatic welding authorship process [9], which provides an opportunity to combine different materials with minimal stresses in the contact zone. Pyrex glass not only has a coefficient of thermal expansion close to silicon but also reduces the number of dislocations in silicon crystal contact zone because of its physical and chemical properties. Reducing the number of dislocations reduces the number of stress regions in the material. Borosilicate glass also has amorphous crystalline structure, so atoms have more freedom to move while energy balance re-establishing in the glass structure. This characteristic of Pyrex glass makes it possible to significantly reduce the internal stresses in the contact zone of glass and metal. The metal layer is the base of proposed flow meter construction. The silicon crystal on the Pyrex glass substrate and conversion board for flow meter sensor Wheatstone bridge scheme and signal data processor are placed directly on the metal layer. The sensor measuring scheme and the conversion board are connected after they are placed on the base layer. The Pyrex glass layer is an isolating intermediate zone which provides an opportunity to reduce
residual stresses cases by the use of different materials while thermal annealing. The combination of base and intermediate isolating layer permits one to increase flow meter sensitivity and decrease the measurement error.

Figure 2. MEMS flow meter 3-D model. (1 - flow meter sensor with Wheatstone bridge scheme, 2 - Pyrex borosilicate glass, 3 - kovar, 4 - conversion board, 5 - contact pads for signal data processor, 6 - conductor).

The flow meter base layer material is kovar. Kovar was chosen as a base layer material taking into consideration the fact that it was designed for combination with glass. Glass and kovar form strong chemical junctions in a thin contact layer after they are connected by presintering or electrostatic welding which helps to minimize dislocations appearance. In addition kovar thermal linear expansion coefficient is close to Pyrex glass coefficient value which improves thermal MEMS flow meter parameters.

Due to flow meter characteristics improvement, new materials for heater and thermistors forming are proposed. According to generalized analyses of different constructional solutions and rigid quality and reliability requirements general requirements for integrating heaters and temperature responsive thermistors were set up [6,10]. The requirements for integrating heaters are:

1. Should be formed on a thin film which coefficient of thermal resistance is not less than 0.3%/°C;
2. The heater should be thermally isolation from the substrate with non-conductive membrane with low thermal conductivity and air gap around it;
3. Non-conductive substrate the heater is placed on should have no internal stresses;
4. The heater material should be chemically stable to external agency or have special chemical protection;
5. The heater material should be temperature resistant and have low coefficient of thermal expansion;
6. Heater material coefficient of thermal expansion should be close to SiO₂ and the substrate values.

A thin pyrolytic silicon film produced by pyrolytic graphite sputter deposition meets all the requirements for integrating heater materials. Sputter deposition method doesn’t change sputtering material structure and characteristics, so the thin pyrolytic silicon film has the same basic characteristics as pyrolytic graphite, including high coefficient of thermal resistance, corrosive environment, and erosion stability, high heat capacity. High heat capacity prevents inertial temperature rise and fall which leads to integrating heater stability.

MEMS flow meter measuring tool are four thermistors with 2.2 kOhm nominal resistance which form the Wheatstone bridge scheme with two measuring and two reference resistors. The two measuring resistors should be placed close to the heater so they could distinctly respond on the temperature change caused by the working fluid rate. The two reference resistors, which balance two legs of Wheatstone bridge scheme, should be placed apart from the flow and have high thermal stability. Nowadays measuring thermistors are made of platinum. However platinum is not only an expensive material but also the process of platinum thin film forming on the Ti underlay is quite complicated. It is proposed to form measuring thermistors from Ni thin film using sputter deposition. To form a thermistor with 2.2 kOhm nominal resistance a 0.3 μm Ni film is needed (Ni surface
resistance is $0.2 \div 0.3 \text{ O}\mu\text{m}$). The length of Ni thermistor should be 40 mm while 0.3 μm thermistor width. Due to the crystal length and width limits, the measuring Ni thermistor should be formed in a complex meander form. For the two reference resistors, thermal characteristics stability is more important than thermal sensitivity. It is proposed to form reference resistors from pyrolytic silicon thin film using sputter deposition method. Pyrolytic silicon film should be not more than 0.3 μm thick.

The electrical scheme displacement on the crystal substrate is shown in figure 3.

**Figure 3.** thermoamemometric flow meter sensor layout plot (1 – contact pad $-U_{in}$ for Wheatstone bridge; 2 – contact pad $U_{out}$; 3 – contact pad $+U_{in}$ for the heater; 4 – contact pad $-U_{in}$ for the heater; 5 – contact pad $+U_{in}$ for Wheatstone bridge; 6 - contact pad $U_{out}$; 7 – thermistor $R_1$; 8 – thermistor $R_2$; 9 – integrating heater; 10 – air gap; 11 – reference resistor $R_3$; 12 – reference resistor $R_4$).

Thermoamemometric flow meter for gaseous working fluids working principle is based on convective working fluid heat transfer from the heater. Thin silicon film with a high coefficient of thermal resistance is used as the heater. Heating is provided by DC current passing through the heater (silicon resistor). The heater temperature is regulated automatically by changing the heater supply voltage value according to the available data. Data acquisition is performed on a test bench to make a plot of the heater temperature and the heater supply voltage. The heater and the Wheatstone bridge scheme have different power supply lines to provide an opportunity of automatic heater temperature regulation.

While gaseous working fluid flows through the resistor $R_1$ to the resistor $R_2$ (fig. 3, pos. 7, 8) convective heat transfer is performed. As a result, the temperature of the thermistor $R_1$ becomes much smaller than the temperature of the thermistor $R_2$. The thermistors temperature change causes the thermistors resistance change. The difference between the resistances $R_1$ and $R_2$ disbalances the legs of Wheatstone bridge which is reflected in the potential difference between $U_{out1}$ and $U_{out2}$ scheme outputs (fig. 3, pos.2, 6). The potential difference increase suggests the increased working fluid flow. Volumetric flow rate of gaseous or liquid working fluids calculation is based on the relationship between flow meter sensor output signal and the temperature difference between thermistors $R_2$ and $R_4$.

3. Conclusion and recommendations

Proposed for consideration thermoamemometric flow meter sensor construction represents one unit, which elements, elements material and even the process of elements forming and manufacturing are combined to improve output signal stability and decrease the measurement error. Platinum integrating heater to silicon film heater change and sputter deposition process simplification would affect the cost of production.

The proposed flow meter sensor construction could be the base for further developments of constructions combining flow meter [2], pressure sensor [5], gas sensor [11-14] and data signal processor on single-crystal silicon crystal to get even more precise measuring results [6,8].
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