Design and analysis of micro thermal mass flow sensor using thin-film-based thermocouples

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Thermopile,
See-Beck Effect,
Calorimetric,
MEMS.

ABSTRACT

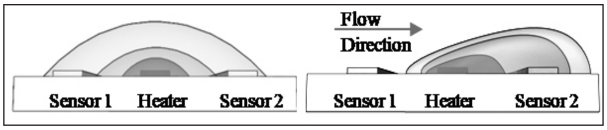
MEMS (Micro-electro mechanical system) based thermal flow sensors are getting more importance due to their ease of fabrication, small size, and high measurement resolution. In this proposed work, a Micro-Thermal flow sensor (TFS) based on MEMS technology is designed using thin film-based thermocouples. This work mainly focuses on materials selection, and identification of fabrication process followed by design, simulation and analysis of Micro-TFS. In this work, Thermopile temperature sensor is selected for Micro-TFS to overcome the drawbacks of other Temperature sensors. Aluminium and Phosphorus materials combination is selected for the Thermopile sensor, which generates a better See-beck coefficient and produces more output voltage. Fabrication process flow based on MEMS technology is identified for Micro-TFS. This proposed flow sensor is capable to measure up to 7 LPM, for a 6 mm diameter channel in Direct-flow mode and up to 110 LPM, for a 25 mm diameter channel in By-pass flow mode.

1. Introduction

The flow sensor market in the emerging economies, such as China, India, and Japan, is expected to grow at the highest CAGR because of the increasing technological advances in medical and healthcare devices due to the increasing population of these countries. Also, the increase in the research and development activities in India and across world has increased the market demand of precise mass flow sensors.

A flow sensor is used to measures fluid flow in the pipes for various applications. The thermal flow sensor which has a heater and two temperature sensors, works on heat transfer principal, the two sensors are arranged on both the sides of heater as shown in the Fig. 1. The flow rate of the fluid passing in the pipe is measured by the Micro-TFS with the help of temperature difference across sensors.

When there is no flow (Fig. 1(a)), the heat from the heater will be transferred to both sensors equally due to conduction. When there is a fluid flow (Fig. 1(b)), the heat from the heater will be transferred due to convection also and pass it to second sensor. Due to this, temperature of second sensor will be higher than first sensor. Hence using these temperature differences, the Micro-TFS measures the fluid flow rate.



a) No fluid flow (b) Fluid flow

Fig. 1. Operating principle of thermal flow sensor (Dou et al., 2015).

As MEMS flow sensors has wide range of advantages and applications in various devices. There is great interest in MEMS flow sensors due to the benefits of miniaturization, low cost, small device footprint, low power consumption, greater sensitivity, integration with on-chip circuitry, etc (Kuo et al., 2012). This results in the replacement of conventional systems which are used in ventilator applications. Mass flow measurement and volumetric flow measurement are most suitable for Micro-TFS as compare to other existing flow measurements. The Volumetric flow measurement depends on size, temperature, and pressure, whereas Mass flow measurement

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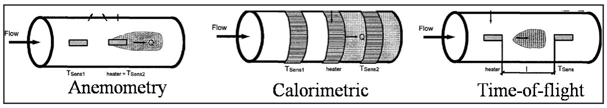

Fig. 2. Forms of thermal flow sensing.

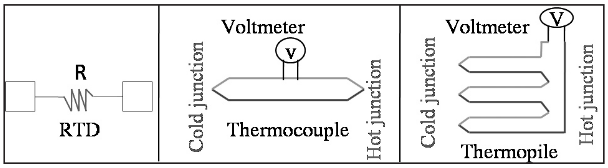

Fig. 3. Temperature sensing mechanisms for micro-TFS.

is independent of these parameters (Kuo et al., 2012). Hence mass flow measurement is considered in this work in order to achieve repeatability and accuracy. As Micro Thermal based flow sensors are mostly preferred for flow measurements because of their advantages like, accuracy, sensitivity and response time, then the existing commercial sensors which are inadequate for precise flow measurement, low response time, etc. Hence Thermal-based MEMS sensor is chosen for the flow measurement (Kim & Kim, 2020).

1.1. Forms of thermal flow sensing

The Micro-TFS majorly works on the three sensing principles i.e., Anemometry, Time-of-Flight, Calorimetric (Fig.2). The Anemometers and Time-of-flight are subjects to surface contamination, have slow response time and are affected by changes in the bulk fluid temperature (Balakrishnan et al., 2017). Whereas the calorimetric flow meter have higher response time and high sensitivity than the other sensing principles. So, to improve response time and sensitivity of Micro-TFS, the calorimetric flow sensing principle is adapted.

The calorimetric flow sensor typically has two temperature sensors installed upstream and downstream of a heater, and the flow rate is calculated based on the temperature differences (Balakrishnan et al., 2017).

1.2. Selection of temperature sensing mechanism for micro TFS

Most commonly used temperature sensors for Micro-TFS are RTD, Thermocouple, and Thermopile (Fig. 3).

- RTD (Resistance Temperature Detector)

The principle of RTD is based on the change of resistance with change in temperature. In RTD to measure the fluid flow, the current is passed through the Hot-wire (Pt100) from the bridge circuit. Then the resistance is produced against the flow of current in hot-wire. When the temperature of the hot-wire increased the resistance also will increases and flow of current through the hot-wire reduces, this change in resistance is used to measure the fluid flow and (Kuo et al., 2012). Here RTD depends on a wheatstone bridge circuit for current supply and to convert output resistance to voltage. These sensors consume a lot of energy and can mechanically deform when moving or accelerating, which has a number of parasitic repercussions (Ashauer et al., 1998).

- Thermocouple sensor

The thermocouple works on See-beck Effect (Kim & Kim, 2020). When ends of two dissimilar conductors or semiconductors are joined to form a hot junction at one end and a cold junction at the other end, and then If the temperature is applied at the hot junction, a voltage is produced in the circuit due to the temperature difference between hot and cold junction. This phenomenon is called as see-beck effect, as shown in Fig. 3.

- Thermopile sensor

A thermopile sensor is an extended version of thermocouples, where several Thermocouples elements are connected in series as shown in Fig. 3 to increase the output voltage. The sensor exhibits a high accuracy, a short response time (<1 ms), and low power consumption (10mW) (Ashauer et al., 1998).

In summary, the Thermopile provides high sensitivity as compare to other temperature sensors. The Thermopile responds faster, when compared to RTD (RTD has a bridge circuit to coverts the resistance, so takes some extra time). The Thermopile sensor is Economical as well because no continuous current supply is required. As the thermopile produces more voltage than Thermocouple & RTD, the Thermopile output will be precise & accurate as compared to Thermocouple & RTD (Ashauer et al., 1998; Balakrishnan et al., 2017; Billat et al., 2007; Dou et al., 2015; Flores et al., 2015; Hedrich et al., 2010; Innovative Sensor Technology IST AG n.a.; Khan et al., 2021; Kim & Kim, 2006; Kuo et al., 2012; Mahvi et al., 2019; Moisello et al., 2021; Zhang & Liao, 2020). Hence the Thermopile based temperature sensing mechanism is used in the proposed work.

2. Selection of Materials

Material combinations used in the previous work Kuo et al. (2012); Kim and Kim (2006); Dou et al. (2015); Zhang and Liao (2020); Flores et al. (2015); Hedrich et al. (2010); Ashauer et al. (1998) for development of Micro-TFS are summarized in Table 1 and their properties in Table 2. The most common material combination for Thermopile sensors are Phosphorus Aluminium and Polysilicon Aluminium. These material combinations are further simulated in ANSYS workbench using thermal electric to find the better output voltage among them, as shown in Fig. 4&5. First the CAD model of single pile of thermopile sensor is designed in SOLIDWORK and imported in to the ANSYS for Simulation. From thermal electric analysis as shown in (shown in the Fig. 4&5), It is clear that aluminium and phosphorus material combination produces better Output Voltage and See-beck coefficient. Hence this material combination is taken for thermopile sensor to improve the accuracy and sensitivity of proposed Micro-TFS.

Table 1
Material combinations of previous work.

Ref. Papers	Upper thermopile Entity	Lower Thermopile Entity	Heater Material
[1]	Alumel	Chromel	Nichrome
[2]	Phosphorus	Aluminium	Phosphorus
[3]	Polysilicon	Aluminium	Polysilicon
[4]	Phosphorus	Boron	-
[5]	Phosphorus	Aluminium	-
[6]	Polysilicon	Aluminium	Polysilicon
[7]	Polysilicon	Gold	Polysilicon

Table 2
Material properties of aluminium, polysilicon, phosphorus.

Materials	See-beck coefficient (µV/K)	Thermal conductivity (W/mK)
Aluminum	-0.165	240
Polysilicon	0.095	25
Phosphorus	0.335	0.235

3. Fabrication Process Flow

MEMS technology is identified for the fabrication of micro thermal flow sensor and process flow is shown in Fig. 6. The initial material is a 524 µm thick, 4-inch diameter n-type silicon double-side polished wafer (Fig. 6(a)). Firstly, a silicon dioxide layer of 200 nm thickness is thermally grown on both side of silicon wafer (Fig. 6(b)) followed by deposition of 150 nm silicon nitride layer using LPCVD (Low pressure chemical vapour deposition) as shown in Fig. 6(c). The multiple lithography processes are performed to fabricate the heater and the temperature sensors (thermopiles) on the

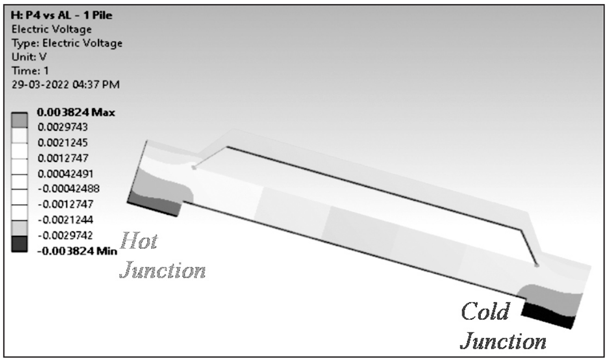

Fig. 4. Phosphorus and aluminium thermal electric simulation results

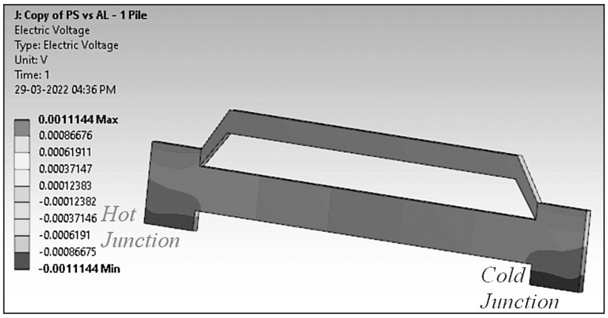

Fig. 5. Polysilicon and aluminium thermal electric simulation results.

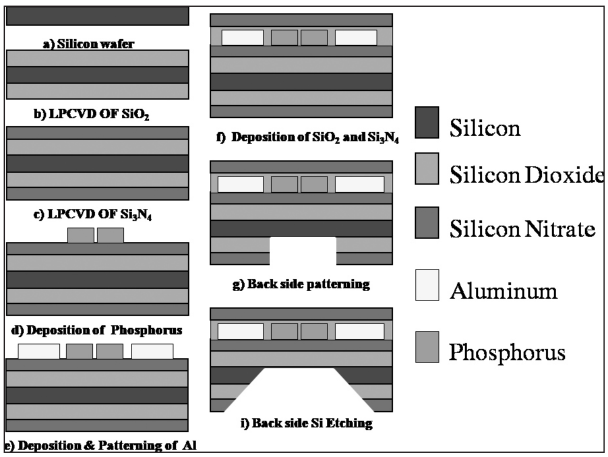

Fig. 6. Complete fabrication process flow of micro-TFS.

wafer. First, 100 nm-thick phosphorus is diffused by LPCVD (Fig. 6(d)). The two heaters and the first half of the thermopiles are then lithographically patterned from this. After this, a 300 nm thick layer of aluminium is patterned to make the other half of the sensor (Fig. 6(e)). Here aluminium is used as another thermopile material as well as for electrical pads and routing.

Afterwards, in order to protect the sensor against harsh environments, a Plasma-enhanced chemical vapour deposition (PECVD) of SiO_2 and Si_3N_4 layers is deposited as a passivation layer on top (Fig 6(g)). The pattering of bottom side SiO_2 and Si_3N_4 is performed (Fig 6(h)) for backside Silicon etching using KOH (Fig 6(i)). The MEMS flow sensor chip is 2 mm wide and 6 mm in length.

4. Designing of Micro-TFS

2D Designing, 3D Modelling, and Assembly of Micro-TFS are done in SOLIDWORKS 2021 software as shown in Fig. 7 and Fig. 8. The complete model of Micro-TFS is designed to achieve better laminar flow rates in the simulations. Initially, a single pile of thermopile sensor is drawn and later 20 thermopile sensors were serially connected to form a thermocouple. Similar thermocouple with 20 thermopile is used on other side of the heater. The heaters, connections, and electrical pads of the Micro-TFS are designed accordingly and also extrudes in to 3D model using commands in the feature tab in solidworks (shown below in Fig.7&8(a)). The bypass flow model is also modelled as shown in Fig. 8(b) the main channel is 25 mm diameter and the bypass channel is 6 mm diameter. The dimensions are taken from the literature survey and modified to our requirement. Finally, the individual parts of Micro-TFS are assembled with By-pass flow channel by importing parts using the 'Insert Component' command in SOLIDWORKS assembly, Fig. 8(b).

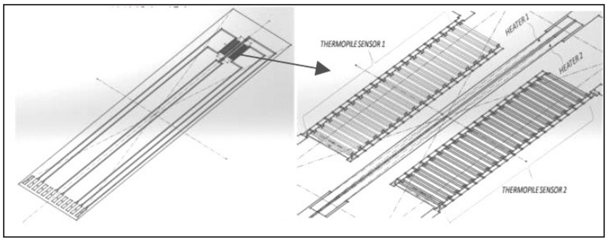

Fig. 7. Isometric view of 2D micro-TFS.

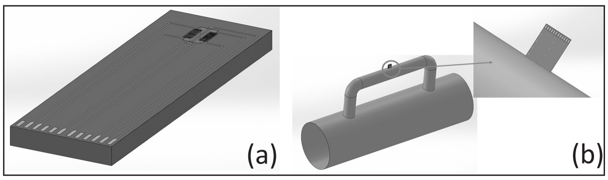

Fig. 8. (a) Micro-TFS, (b) Bypass flow model and micro TFS assembly.

5. Simulation and Analysis

Fluent simulation with ANSYS workbench is chosen for better flow simulation and analysis of designed Micro-TFS. Fluent analysis and simulation are carried out on direct flow model and by pass flow model for different flow rates in order to achieve the better laminar flow rates.

5.1. Direct flow simulation

Fluent simulation of direct flow model (Fig. 9&10) is carried out for different flow rates with ANSYS workbench for laminar flow and the simulation results were analysed. It is observed that the Micro-TFS installed in a 6 mm diameter direct flow model can measures up to 7 LPM accurately due to laminar flow and after 7 LPM Turbulence flow is occurring which generates in-accurate flow simulation results.

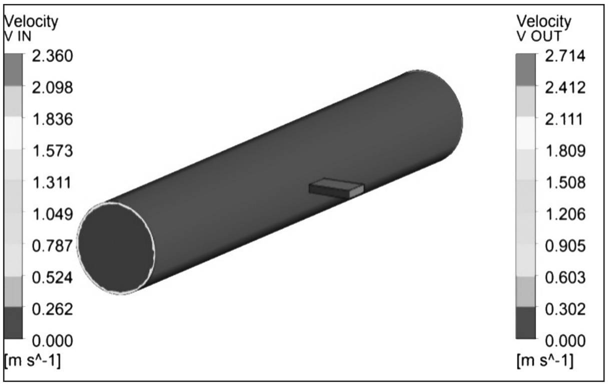

Fig. 9. Velocities of inlet & outlet in direct flow model simulation.

Fig. 10. Zoom-in view of the sensors inside the fluid flow, shows temperatures of sensor 1 & sensor 2 in direct flow model simulation.

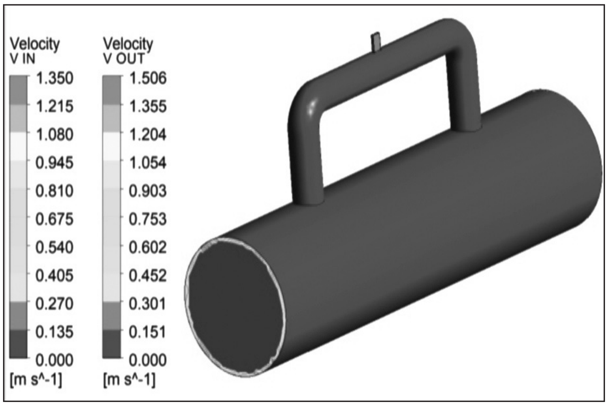

Fig. 11. Velocities of inlet & outlet in bypass flow model simulation.

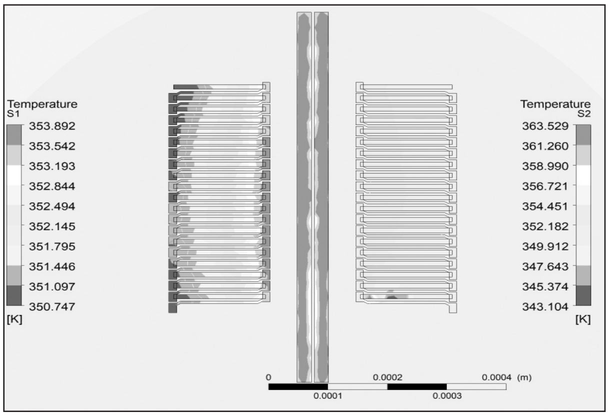

Fig. 12. Zoom-in view of the sensors inside the fluid flow, shows the temperatures of sensor 1 & sensor 2 in bypass flow model simulation.

5.2. Bypass flow simulation

In a similar way, Fluent simulation is done on a By-pass flow model (Fig.11&12) for different flow rates in Ansys workbench. It is observed that the Micro-TFS installed in a By-pass flow model of 25 mm diameter channel can measure up to 110 LPM in laminar flow.

6. Conclusion

Thermopile based Micro-TFS was designed based on calorimetric flow sensing principle to achieve fast response, high sensitivity and better accuracy. Phosphorus and aluminium materials are selected for fabrication of thermopiles based on thermal electric simulation results to improve sensitivity due to high sees-back effect. The complete flow sensor is designed using MEMS fabrication technology. The ANSYS Fluent simulation was carried out for both direct and bypass flow models to obtain laminar flow in the flow channel for better flow detection. Direct flow mode can measure up to 7 LPM where Bypass flow mode can measure up to 110 LPM. The fabrication of this proposed sensor is under progress.

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