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Thermal pressure high temperature gradient micro-sensor for aerodynamic measurements

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Abstract

This paper presents a thermal based micro-sensor designed for pressure measurements for application in aerodynamics. The sensor is a thermistor based transducer operating with the Pirani effect, exploiting the pressure-dependency of the thermal conductivity of a gas. The sensor presents a wide measurement range between 10 kPa and about 800 kPa, in both constant current and constant temperature mode. It reached in CT mode high-sensitive measurements with a maximum of sensitivity around atmospheric pressure. It is therefore valuable for applications in aerodynamics and fluid dynamics, like active flow control.

1. Introduction

The knowledge of pressure is very important in aeronautics (e.g. flow control on vehicles, wall pressure measurements) and aerospace applications (e.g. vacuum quality check for spatial sensors) [1]. With microtechniques, pressure sensors were developed with objectives of miniaturization, for less impact on the measured system, and efficiency, depending on the pressure range considered. Various physics principles have been used to design pressure micro-sensors including piezoresistivity [2], piezoelectricity [3], capacitance [4], or thermal sensors [5,6]. On thermal sensors, the approach is based on the Pirani effect that consists in measuring the pressure-dependent thermal conductivity of the gas surrounding the sensor when the gas is in molecular flow regime. Pirani-based sensors have no moving part and are relatively easy to fabricate and miniaturize. In most cases however, Pirani-based sensors only operates in range below atmospheric pressure [6], for vacuum or extreme vacuum sensing, but a Pirani sensor operating around and above atmospheric pressure range is a potential substitute for membrane-based pressure sensors [5].

We present an original Pirani MEMS sensor designed for aerodynamics and flow control applications. The micro-fabrication process is CMOS-compatible allowing on-chip integration for designing very small devices. The sensor structure consists in a hot-wire, suspended over the substrate, and mechanically supported using periodic micro-bridges. With such a structure, the wire achieves 1 mm long for only 3 µm wide and it is suspended over a constant 150-nm-high gap. This design enables pressure measurements around atmospheric pressure, and grants a homogeneous temperature uniformity along the wire and a high temperature gradient transversally to the wire.
This paper presents the Pirani effect on which the micro-sensor is based.
Pressure measurements were performed in a pressure-controlled environment, in a range going from 10 kPa to 800 kPa. The sensor could operate in 'constant temperature' (CT) mode, with a feedback on the heating current. Results showed the sensor high sensitivity with a maximum at atmospheric pressure [7].

2. Pirani based pressure sensors

Marcello Pirani invented the Pirani gauge in 1906. It was then made of a thermoresistive hot wire (filament) placed in an enclosure whose pressure is to be measured. The operating principle is based on the fact that the heat transfer between two surfaces is proportional to the number of gas molecules (therefore to pressure) transferring heat, if the mean free path of gas molecules is wider than the distance between the two surfaces. At high pressure, the thermal transfer by collision of the gas molecules on the filament is completely efficient, not allowing the measurement of the pressure (first saturation state). When the pressure decreases, the mean free path of the gas molecules increases and becomes of the same order of magnitude as the filament. At this pressure called pressure of transition, the thermal transfer by collision of the gas molecules becomes less efficient and the thermal conductivity of the gas decreases until the mean free path of the molecules is sufficiently wide to thermally isolating the filament (second saturation state).

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Finally, the evolution of the thermal conductivity with the logarithm of pressure takes a S-shape representing the three states (Figure 1). The transition zone is the one used for the measurement of the pressure.

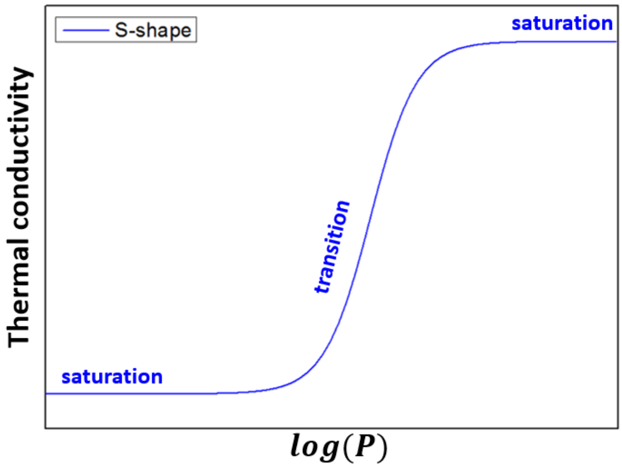

Figure 1: S-shape curve of gas thermal conductivity as function of pressure

With micro-technologies, the structure of the Pirani sensor evolves towards a design associating a hot wire and a heat sink, the substrate, the first being separated from the second by a space called the gap. The operating principle remains that of heat transfer, depending on the pressure, of the hot wire suspended on the substrate, through the gap.
Mastrangelo and Muller propose an analytical model to better understand the operating mode of the micro-bridge Pirani gauge [7]. In this model, the temperature variation along the micro-bridge, $u(x) = T(x) - T_s$ evolves according to the stationary heat equation:

$$\frac{\partial^2 u}{dx^2} - \epsilon u + \delta = 0$$

with $T(x)$ the bridge temperature, T_s the temperature of the substrate, ϵ the heat losses in the gas included in the gap and δ the generated ohmic power. More precisely, since the wire is thermoresistive, the expression of the resistance of the wire R_b is deduced as a function of the pressure p:

$$R_b = R_0 \left[1 + \frac{\delta\, TCR}{\epsilon} (1 - \frac{\tanh\left(\frac{\sqrt{\epsilon}L}{2}\right)}{\frac{\sqrt{\epsilon}L}{2}}) \right]$$

with

$$\frac{R_b - R_0}{R_0} = TCR\, \Delta T$$

$$\delta = \frac{i^2 R_0}{k_b w L t}$$

$$\epsilon = \frac{k_g(p)}{k_b g t} - \delta\, TCR$$

The pressure dependency is expressed by the effective thermal conductivity of the gas contained in the gap k_g :

$$k_g = k_{g0} \frac{p/p_t}{1 + p/p_t}$$

where p is the absolute pressure, p_t is the transition pressure and k_{g0} is the high-pressure thermal conductivity value. The transition pressure determines the sensitivity range of the micro-sensor and can be approximated by:

$$p_t = \frac{k_{g0} w T_s}{(w + t) g \bar{v}}$$

with w the width of the bridge wire, t its thickness, g the gap height and $\bar{v}$ the mean molecular velocity.
The design of the Pirani sensors is related to the target application, in particular the pressure range that we are trying to detect, and it depends mainly on two geometrical parameters: the length of the hot wire and the gap. By increasing the length of the wire, sensitivity to low pressures is improved, as well as thermal uniformity along the wire (increasing the aspect ratio of the wire). Indeed, for a low pressure, there are few atoms / molecules in the gas, so the average free path is wider than the gap. this means that the molecules present collide with the bridge and carry the heat. The pressure will be less sensitive to the gap height than the surface of the heating element, so the length of the bridge. Conversely,

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when the pressure increases, the mean free path decreases and that is why to increase the interaction between the gas and the bridge, the gap must be decreased. For a given overheat, the transition pressure shifts to high pressures when the gap decreases.

Given that, Pirani sensors are usually divided into two categories ([8,9]): micro-beam structures and resistors on dielectric membrane.

Micro-beam structures present a wire resistor fixed at both extremities and suspended over the substrate. The fabrication process and the scaling down are simple, enabling the fabrication of nanowire sensors ([6,10,11]). These sensors, with nanoscale gap and microscale length, are suitable for near atmospheric pressure measurements. However, the length is limited due to buckling issues implying that the measurement range is shortened.

For resistors on dielectric membranes, a serpentine thermistor, made of metal [12] or poly-Si [9], is deposited on a dielectric membrane, suspended over the substrate. These sensors present a higher mechanical toughness against collapse and the increased heat exchange surface improves measurements in the low pressure range. However, the gap, made with back-side bulk machining techniques, is difficult to control and to decrease to nanoscale for measurements within the atmospheric range. These sensors are indeed mostly suitable for low to vacuum pressure measurements in a wide dynamic range.

3. High temperature gradient Pirani micro-sensor

In this section, we present a nanogap Pirani sensor demonstrating high sensitive pressure measurements both in a wide range and around atmospheric pressure.

The design, made of a high aspect ratio wire suspended over the substrate using perpendicular micro-bridges for mechanical support, takes advantages from both kinds of usual Pirani sensors. It is structured as an array of micro-Pirani gauges assembled in series (**Erreur ! Source du renvoi introuvable.**). Each micro-Pirani gauge cell behaves as a micro-beam Pirani sensor: a 3 µm wide and 8 µm long wire is free from the substrate over a nanoscale gap and anchored on both extremities to perpendicular 2 µm wide SiO2 micro-bridges, also separated from the substrate by the gap. The nanoscale gap and the microscale length of the unit cell, provide high pressure measurement and high sensitivity near the atmospheric pressure.

The wire is nanostructured with multiple layers, SiO_2/Ni/Pt/Ni/Pt/Ni/SiO_2/Ti/Au, reaching a total thickness beyond 1 µm. Measurement and heating are uncoupled to improve the signal to noise ratio: the measurement is realized through the Ni/Pt multilayer and the heater is composed of Ti/Au. The SiO_2 layers isolate the measurement wire from the heater and strengthen the structure.

This single cell structure is duplicated 100 times to reach 1 mm long. The high aspect ratio of the wire allows a uniform heating profile along the wire and the extended heat exchange area provides sensitivity in the low pressure range. The periodic micro-bridges ensure mechanical toughness against collapse, like the membrane in case of resistors on dielectric membrane.

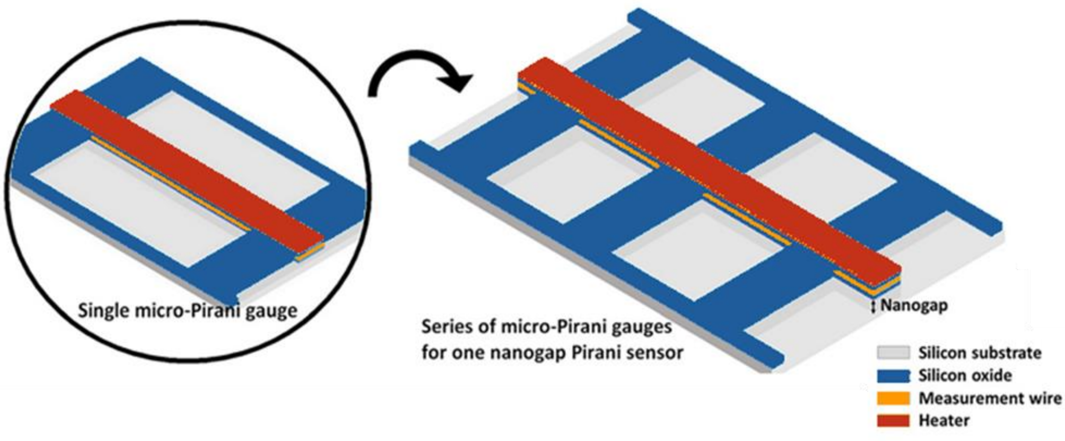

Figure 2 Schematic of the Pirani based high temperature gradient micro-sensor [13]

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The design results in a structure combining a nanoscale gap, for near atmospheric pressure measurements, a long wire length acting in the low pressure range, and a shorter effective length, engineered with the heat leakage in the bridges, acting the high pressure range and providing a high sensitivity near atmospheric pressure.

The sensor is designed to work in both constant current (CC) and constant temperature (CT) modes. In the CC mode, the pressure is inferred by using the temperature-dependence of the wire resistance. The Ni/Pt multilayer (sensitive element) was chosen for its high sensitivity to temperature. In the CT mode, a feedback on the heating current adjusts it to ensure that the temperature along the wire remains constant. The pressure is inferred from the measure of the current variations.

The CT mode is more difficult to implement than the conventional CC mode, due to the necessary feedback on the heating current. However, it allows to work at the maximum efficiency at atmospheric pressure, it protects the wire integrity at low pressure, enabling to extend the dynamic range, and, like feedback systems, it increases the resolution and the sensitivity.

We manufactured the micro-sensor using surface micro-machining techniques. Five major CMOS-compatible steps are necessary to process simultaneously more than a hundred of sensors on a 3-inches wafer. Figure 3 (a) and Figure 3 (b) are Scanning Electron Microscopy (SEM) pictures of the manufactured sensors. Figure 3 (c) is a cross-section SEM picture allowing a precise measurement of the nanogap of 170 nm. It corresponds to a cross view localized at the yellow dotted line.

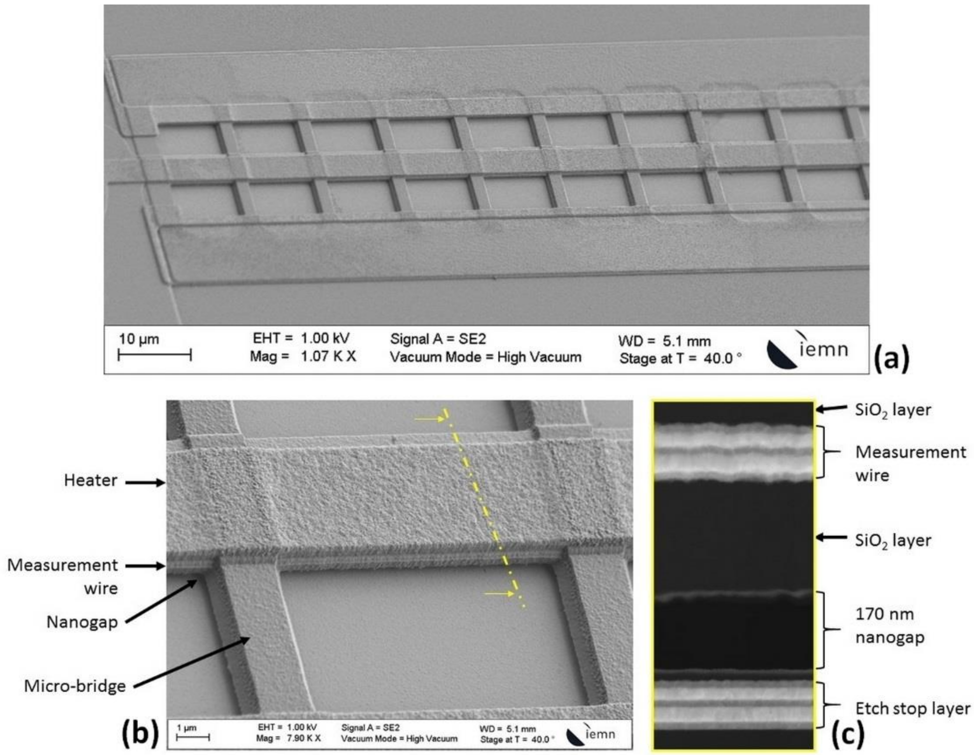

Figure 3 a) SEM picture of the manufactured nanogap Pirani micro-sensor (b) Zoom on the suspended wire (c) Cross section SEM picture with zoom on the nanogap [13]

4. Tests in pressure-controlled environment

The purpose of the Pirani pressure micro-sensors is to measure the absolute pressure in a given environment, and more precisely in aerodynamic flows. In order to perform their calibration, they were tested in a controlled pressure environment. The experimental setup, shown in Figure 4 therefore comprises a pressure chamber, a hermetically sealed environment in which the micro-sensor is inserted. The pressure inside the chamber is controlled by a PPC4 Fluke Calibrator Pressure Calibrator, controlled by the control computer and a program run on LabVIEW. The micro-sensors were first tested using the HTGS test bench, the first electronic developed by Fluiditech / Thurmelec's Romain VIARD. A sensor Kulite brand is also integrated into the pressure chamber to ensure a reference.

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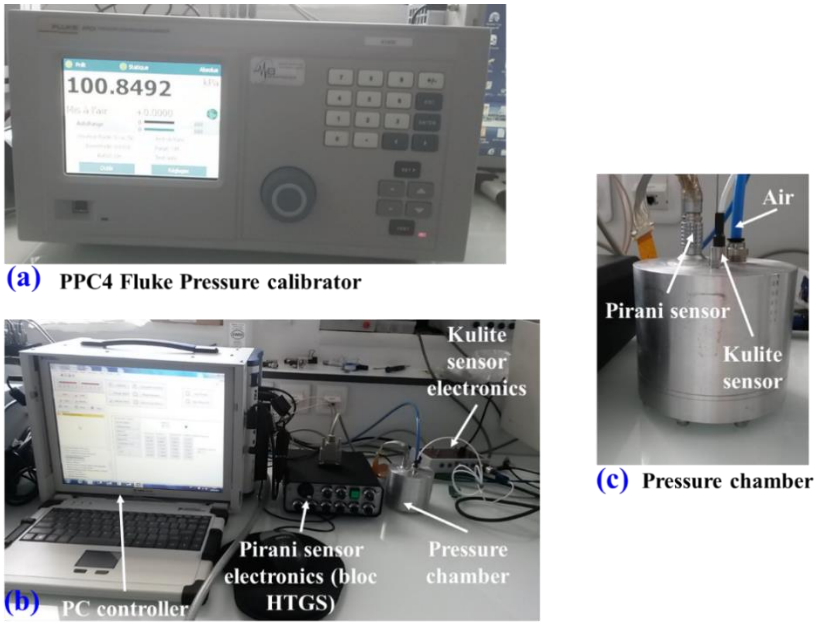

Figure 4: Experimental setup: (a) PPC4 Fluke Calibrator Pressure Calibrator (b) Control Computer, Electronic Sensor Conditioning (c) Pressure Chamber

Calibrations of the pressure micro-sensor were performed in constant current (CC) and constant temperature (CT) mode.

In CC mode, the micro-sensor is heated with a power of 9.5 mW, corresponding to an overheat of 20°C at atmospheric pressure. The variation of resistance of the wire with the pressure is measured for pressure values ranging from 10 kPa to 800 kPa. The resistance variations are measured with respect to the resistance value at atmospheric pressure according to the expression:

$$Resistance\ variation = \frac{R\ (x) - R\ (P_{atm})}{R\ (P_{atm})}$$

The results presented in Figure 5 (a) show a sensitivity to pressure over the two decades considered. For pressures below atmospheric pressure, the wire temperature increases, leading to a positive resistance variation. For larger pressures, the temperature decreases, leading to a negative resistance variation. The results show a high sensitivity to atmospheric pressure, although the pressure range for which the micro-sensor is most effective is rather below atmospheric pressure. Indeed, from 200 kPa the micro-sensor begins to saturate, while at the other end, at 10 kPa, the micro-sensor is still in its optimal operating range. The maximum sensitivity of the device is reached for about 50 kPa.

In CT mode, the hot micro-wire is maintained at a temperature of 20 ° C by the control circuit. The results obtained are shown in Figure 5 (b). The latter this time expresses the current variations, with respect to the current applied at atmospheric pressure, as a function of the pressure under consideration. The response therefore varies inversely with respect to the CC mode. Indeed, since the temperature increases for low pressures, the current itself decreases to maintain the wire at 20 ° C. On the contrary, at high pressure, the current increases. The experimental results show at first glance a quite different evolution between the CC mode and the CT mode. Consequently, the Pirani micro-sensor has a maximum sensitivity around the atmospheric pressure when it is used in CT mode. In addition, the amplitude of the variations is considerable which allows a high resolution of the measurement. Moreover, although the shape of the response has slope changes, the micro-sensor does not reach, in this mode of operation, any of its saturation limits, or low pressure or high pressure.

All in all, the results obtained with this thermal based pressure sensor are promising for aerodynamic pressure measurements. Further work will focus on implementing the micro-sensors in wind tunnel for wall pressure measurements.

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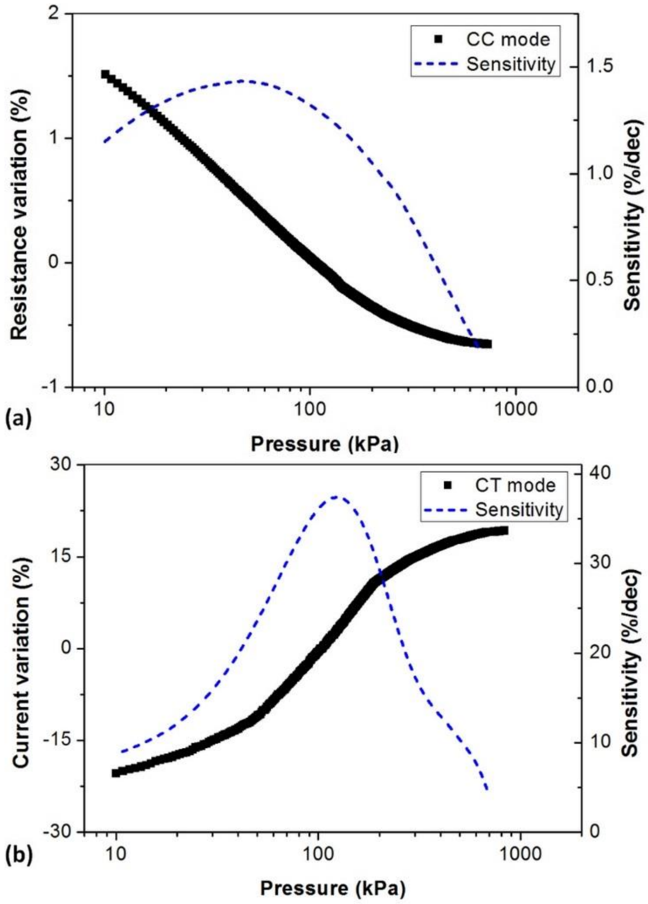

Figure 5: Nanogap Pirani micro-sensor response to pressure from 10 kPa to 800 kPa, when operating in CC mode (a) and CT mode (b)

5. Conclusion

This paper presented and described the design and testing of an efficient and high sensitive pressure sensor based on the Pirani effect. The original structure of the sensor enabling the fabrication of a long hot-wire suspended over a nanoscale gap, allows high sensitive measurements in a wide range around atmospheric pressure. With pressure ranging from 10 to 800 kPa, the sensor has not reached its saturation limits, implying a higher dynamic range. The maximum of sensitivity is reached for a pressure near the atmospheric pressure. Further characterization will investigate the dynamical behavior of the sensor and its response to an aerodynamic flow in a wind tunnel.

Acknowledgements

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