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Nanogap Pirani Sensor Operating in Constant Temperature Mode for Near Atmospheric Pressure Measurements †

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Abstract: This paper presents a high sensitive micro-sensor designed for pressure measurements in a wide range around atmospheric pressure, for application in aerodynamics. The sensor is a temperature-resistance transducer operating with the Pirani effect, which states that below a certain pressure limit, the thermal conductivity of a gas is pressure-dependent. The sensor presents a wide measurement range between 10 kPa and about 800 kPa, in both constant current and constant temperature mode. The last mode enables high-sensitive measurements with a maximum of sensitivity around atmospheric pressure, enabling the use of the sensor for applications in aerodynamics and fluid dynamics, such as active flow control.

Keywords: MEMS sensors; pressure sensors; pirani sensors; flow control

1. Introduction

Pirani gauges are widely used in vacuum equipment [1]. In 1906, Marcello Pirani invented it using a temperature-dependent resistor in vacuum tube. With the development of microelectronics and micro-electromechanical systems techniques, the Pirani gauges were subject to miniaturization, as reported in numerous papers [1–3]. Micromachined Pirani sensors consist in a hot-wire, the heater, suspended over a heatsink, the substrate, by a gap. The electrical current applied and the heat transfer through the surrounding gas determine the heater temperature. In vacuum, the heater is thermally isolated from the substrate, except at the extremities where the wire is bound. The temperature is determined by the heating current applied. At higher pressure, there are more gas molecule in contact with the heater, increasing the heat transfer, and the heater temperature decreases in consequence. This phenomenon goes on up to a maximum pressure limit, for which the heat transfer is saturated. Between the minimum and the maximum pressure limits, the thermal conductivity of a given gas is thereby pressure-dependent and directly affects the heater temperature. The measurement of the heater temperature, by means of the measurement of the wire resistance, becomes then the value of pressure. This upper pressure limit is conditioned by the gap size in Pirani sensors: the pressure-dependence of thermal conductivity occurs when the gap is near the mean free path of the gas molecules. For sensing pressure near the atmospheric pressure, the gap has to be decreased to a nanoscale [2,4]. However, when the gap size reduces to sub-micron scale, the fabrication process is more complex: the size of the wire has to be decreased as well to avoid collapsing of the structure onto the substrate [3]. The length of the wire reduces to microns and the diameter to nanoscale. Therefore, high expensive techniques are used, like ion-beam prototyping technique [5] or e-beam and deep UV lithography [3]. Moreover, the sensitivity of a Pirani gauge is proportional to the heat exchange area and Pirani sensors with microscale and nanoscale geometrical parameters suffer from a decreased sensitivity.

In this communication, we present a surface-micromachined Pirani sensor consisting in a long thermistor suspended over a constant nanoscale gap and supported by transversal periodic micro-bridges. The wire is 1 mm long and 4 μm wide, enabling the use of conventional photolithography techniques and allowing high sensitivity. The transversal micro-bridges ensure mechanical support against collapsing. The gap is engineered using sputtered 100 nm high silicon sacrificial layer. The sacrificial layer is etched using Xenon Difluoride in the final step of the process to release the structure (the hot-wire and the micro-bridges). The sensor was characterized in a pressurized environment from 10 kPa to 800 kPa, and exhibits a high sensitivity in a wide range around atmospheric pressure.

2. Sensor Design

The sensor's original structure consists in using silicon oxide micro-bridges to support a high aspect ratio hot-wire. This structure has been patented by the IEMN LIA LICS and then tested in different configurations: as a flow sensor [6], a wall shear stress and flow direction sensor [7,8], and as a pressure sensor, using the Pirani effect. The pressure sensor consists then in a 1 mm long and 4 μm wide wire structured with multiple layers (Figure 1). On top there is the heater, the metallic layer supplied with electrical current in the range of 0–10 mA, for heating the wire by Joule effect. Between two layers of silicon oxide, there is a metallic layer for measurement: made of Ni/Pt alloy, this layer is only supplied by a 100 μA current for measuring the resistance value using the 4-points technique (Figure 2). The layer of silicon oxide between the two metallic wire electrically insulate the heating part and the measurement part of the wire, and the layer of silicon oxide at the bottom strengthens the structure.

The perpendicular and periodic micro-bridges are made of silicon oxide as well. Silicon oxide presents an efficient thermal insulation limiting heat losses by thermal conduction. Even if the wire is periodically crossed by the micro-bridges, the heating remains relatively uniform along the wire, as if it was a conventional micro-beam structure, fixed on both extremities. The micro-bridges nonetheless affect the mean temperature by decreasing it a little comparing with a micro-beam structure with the same geometrical dimensions. However, such a structure is not realizable over a nanoscale gap because, due to buckling, the wire would collapse onto the substrate.

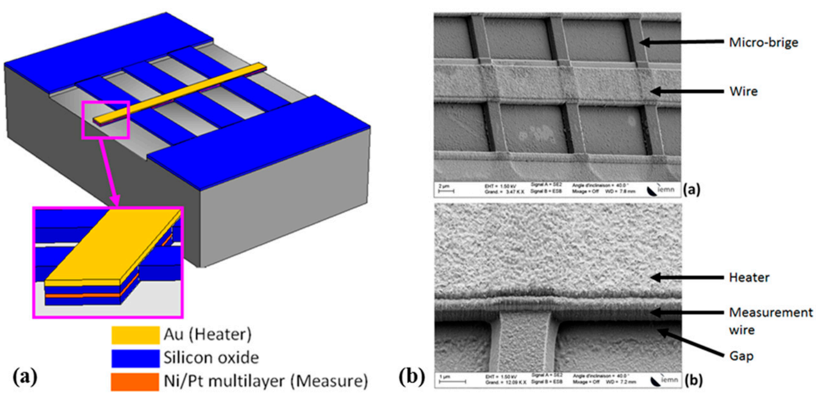

Figure 1. (**a**) Schematic of the Pirani sensor (**b**) SEM pictures of the manufactured sensor.

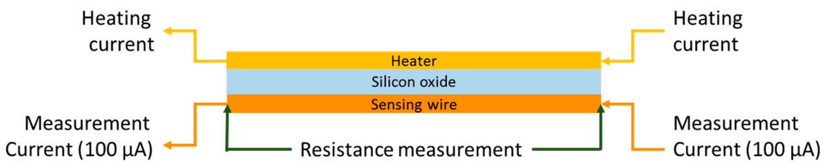

Figure 2. Schematic of the uncoupling between heating and measure, and of the 4-points technique for sensing resistance measurement.

3. Fabrication Process

The fabrication process of the sensor needs six masks and is composed of ten CMOS-compatible steps, summarized in Figure 3. The four first steps aim at preparing the gap: first, a layer of silicon oxide is deposited, then a metallic layer is patterned at the gap location as a stop-etch layer, next another layer of silicon oxide is deposited and etched to form a cavity in which the 200 nm high silicon sacrificial layer is sputtered. Afterwards, the suspended wire is realized: the measurement thermistor, the layers of silicon oxide and the heater. In views (i) and (j), two cross-sections are shown: on the left, the cross section at a location where there is no micro-bridge, and on the right, where there is a micro-bridge.

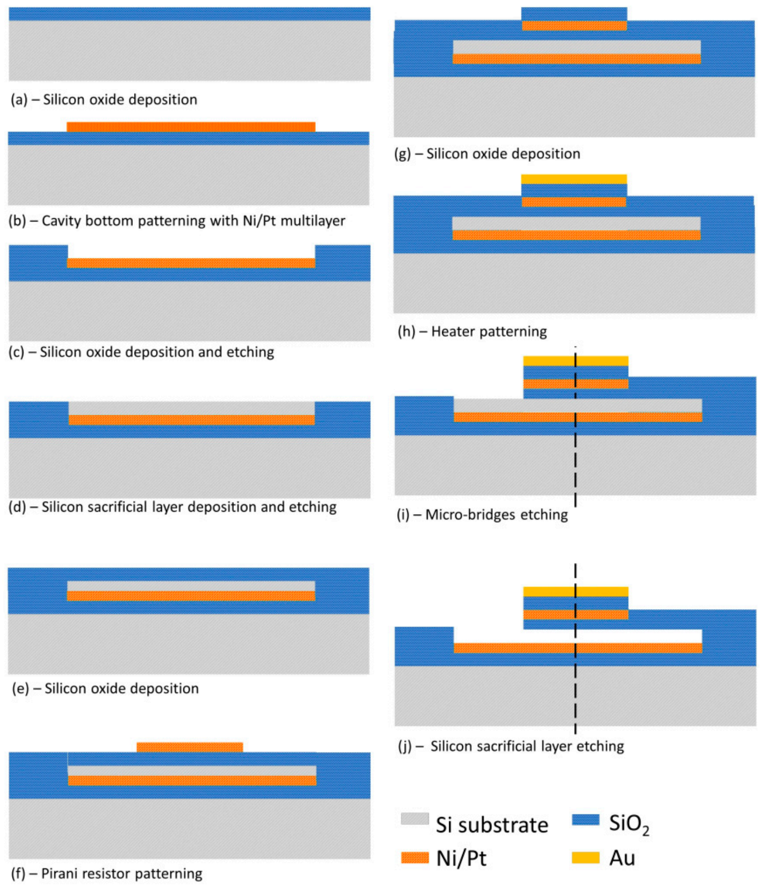

Figure 3. Fabrication process.

4. Characterizations in Pressurized Environment

The sensor was then characterized in a pressurized environment using a PPC4 Fluke pressure calibrator that controls the pressure value inside the chamber. The experiments were conducted sing the sensor in constant temperature (CT) mode, with pressures ranging from 10 kPa to 800 kPa. The CT mode maintains the temperature of the measurement wire constant. To achieve that, the heating current is adapted to let the resistance value of the measurement wire constant. The results, presented in Figure 4, show the high sensitivity of the sensor, with a maximum reached for a pressure near the atmospheric pressure. They highlight the usefulness of the structure with both a high sensitivity and maximum efficiency around atmospheric pressure. Moreover, even if the curve starts to bend at low and high pressure, the sensor does not reach the pressure saturation limits, neither at low nor at high pressure.

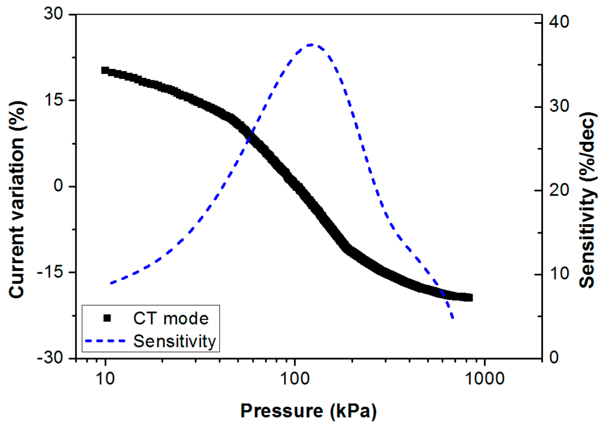

Figure 4. Output of the sensor in % versus pressure ranging from 10 to 800 kPa.

5. Conclusions

This paper presents and describes 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.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, F.T.; Tang, Z.; Yu, J.; Jin, R.C. A micro-Pirani vacuum gauge based on micro-hotplate technology. *Sens. Actuators Phys.* **2006**, *126*, 300–305.
2. Khosraviani, K.; Leung, A.M. The nanogap Pirani—A pressure sensor with superior linearity in an atmospheric pressure range. *J. Micromech. Microeng.* **2009**, *19*, 045007.
3. Brun, T.; Mercier, D.; Koumela, A.; Marcoux, C.; Duraffourg, L. Silicon nanowire based Pirani sensor for vacuum measurements. *Appl. Phys. Lett.* **2012**, *101*, 183506.
4. Claudel, J.; Ghouila-Houri, C.; Gerbedoen, J.C.; Gallas, Q.; Garnier, E.; Merlen, A.; Elmazria, O.; Viard, R.; Talbi, A.; Pernod, P. High Resolution Nano-gap Pirani Sensor for Pressure Measurement in Wide Dynamic Range Operation Around Atmospheric Pressure. *Procedia Eng.* **2016**, *168*, 798–801.
5. Puers, R.; Reyntjens, S.; De Bruyker, D. The NanoPirani—An extremely miniaturized pressure sensor fabricated by focused ion beam rapid prototyping. *Sens. Actuators Phys.* **2002**, *97*, 208–214.
6. Viard, R.; Talbi, A.; Merlen, A.; Pernod, P.; Frankiewicz, C.; Gerbedoen, J.C.; Preobrazhensky, V. A robust thermal microstructure for mass flow rate measurement in steady and unsteady flows. *J. Micromech. Microeng.* **2013**, *23*, 65016.

7. Ghouila-Houri, C.; Claudel, J.; Gerbedoen, J.C.; Gallas, Q.; Garnier, E.; Merlen, A.; Viard, R.; Talbi, A.; Pernod, P. Wall Shear Stress and Flow Direction Thermal MEMS Sensor for Separation Detection and Flow Control Applications. *Procedia Eng.* **2016**, *168*, 774–777.
8. Ghouila-Houri, C.; Claudel, J.; Gerbedoen, J.C.; Gallas, Q.; Garnier, E.; Merlen, A.; Viard, R.; Talbi, A.; Pernod, P. High temperature gradient micro-sensor for wall shear stress and flow direction measurements. *Appl. Phys. Lett.* **2016**, *109*, 241905.