



HAL
open science

Very high aspect ratio hot-wire based MEMS thermal sensor for near wall turbulent flow measurement with high sensitivity and low power consumption

Cécile Ghouila-Houri, J. Claudel, J.C. Gerbedoen, Q. Gallas, E. Garnier, A. Merlen, R. Viard, Abdelkrim Talbi, Philippe Pernod

► To cite this version:

Cécile Ghouila-Houri, J. Claudel, J.C. Gerbedoen, Q. Gallas, E. Garnier, et al.. Very high aspect ratio hot-wire based MEMS thermal sensor for near wall turbulent flow measurement with high sensitivity and low power consumption. 2016. hal-01396294

HAL Id: hal-01396294

<https://hal.science/hal-01396294>

Preprint submitted on 16 Nov 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Very high aspect ratio hot-wire based MEMS thermal sensor for near wall turbulent flow measurement with high sensitivity and low power consumption

C. Ghouila-Houri,^{1,2, a)} J. Claudel,¹ J-C. Gerbedoen,¹ Q. Gallas,² E. Garnier,² A. Merlen,¹ R. Viard,³ A. Talbi,¹ and P. Pernod¹

¹⁾ *Univ. Lille, Centrale Lille, LIA LICS/LEMAC - IEMN UMR CNRS 8520, 59000 Lille, France*

²⁾ *ONERA, Chemin de la Hunire 91123 Palaiseau, France*

³⁾ *Fluiditech, Thurmelec, 68840 Pulversheim, France*

(Dated: 26 September 2016)

We present an efficient and high-sensitive micro-electro-mechanical system (MEMS) thermal hot-wire based flow sensor for near wall flow measurement. By combining substrate-free wire structure and mechanical support by silicon oxide micro-bridges, the sensor wires achieve a very high aspect ratio, superior to 300, with 1 mm long for only 3 μm wide. The sensor is designed for compromising conventional hot-film and hot-wire sensors and to achieve high sensitivity to the near wall flow velocity, fast response time and flow direction detection. The sensor can be mounted flush to the wall for technical application, such as flow control and separation detection, or for understanding near wall shear flows. We present here the design and micro-fabrication, then electrical and thermal characterizations and finally the first experiments in a turbulent boundary layer wind tunnel.

Keywords: MEMS hot-wire sensors; Wall shear-stress sensor; Turbulence analysis; Separation detection; Flow control

Accurate near wall flow measurement plays a key role for technical applications such as flow control in domains including aerospace, aeronautics, micro-fluidics, or process control, and for the understanding of unsteady flows and turbulence. When measuring fluctuations quantities in high Reynolds number turbulent boundary layers, flow sensors have to resolve both small length- and velocity-scales and high frequencies, in the view of Kolmogorov scales¹. For instance, considering an airplane flying at 230 m/s with the wing chord of about 3 m, the Reynolds number is about 50×10^6 and the resulting l_{min} is about 5 μm . Therefore very small, fast and high sensitive measurement devices are needed and Micro-Electro-Mechanical Systems (MEMS) technology allows the development of miniaturized flow sensors that can fulfill such requirements in terms of high spatial and temporal resolutions performances as well as low-cost mass production and high reliability.

Micro-machined flow sensors can be classified into two groups based on different measurement methods: 'direct' or 'indirect' measurement sensors². The first ones usually use a floating element displaced laterally by tangential viscous forces in the flow and the movement implies a variation of an electrical parameter: capacitive sensors³ or cantilever based sensors⁴ are part of this category. For indirect flow measurement, various methods have been applied as for examples, micro-fences using a cantilever structure and piezoresistors⁵, optical resonance such as whispering gallery modes of dielectric microspheres shifted with radial deformations of the spheres due to the shear stress⁶, the deflection of

micro-pillars⁷ and thermal-based sensors, which are developed below. Among all these devices, thermal sensors are widely adopted when dealing with fluids dynamics including laminar or turbulent flows as they do not contain mechanical moving parts and are thus less prone to wear than the others.

Thermal flow sensors are themselves classified into two categories: hot-wires sensors and hot-film sensors. The difference between them lies in the designed structure: in hot-wire sensors the metallic wire resistor is free from the substrate and placed within the flow whereas in hot-film sensors it is deposited on a membrane placed adjacent to the flow. Hot-film sensors suffers from heat losses in the membrane on which the metallic wire is deposited: various materials have thus been used and we report hot-film sensors made on silicon nitride⁸, glass^{9,10} or flexible polymer^{11,12}. These sensors are nonetheless often used for flow separation detection and wall shear stress measurement as they are robust and easy to mount flush to the wall. Hot-wire sensors are more fragile than hot-film sensors. The wire is mainly free from the substrate which enable an optimal heating uniformity and high sensitivity^{13,14,15}.

In this letter we present a thermal sensor designed for flow control applications and separation detection whose structure is a compromise between conventional hot-wires and hot-film sensors. In our case, the heating and measurement elements consist of very high aspect ratio metallic wires free from the substrate over a 20 μm deep cavity and suspended by periodic silicon oxide micro-bridges. This design allows efficient thermal insulation as well as mechanical robustness. The sensor operates in constant current anemometric mode or constant temperature anemometric mode and is sensitive

^{a)} Electronic mail: cecile.ghouila@onera.fr

to near wall flow variations (velocity, wall shear stress) and flow direction. The sensor design is patented by the IEMN LIA LICS/LEMA^{16, 17}.

The device geometry (Fig.1 (a)) consists in four 1-mm-long and 3- μm -wide free from the substrate wires supported by silicon oxide micro-bridges over a 20- μm -deep cavity: one is the heater and the other three are measurement wires. The heater is over a sensitive wire: they form a multilayer at the center of the sensitive part with a layer of silicon oxide ensuring electrical insulation between them. Measure and heating are electrically uncoupled to improve the signal to noise ratio. The other sensitive wires are arranged on both sides of this central element. Each wire is separated from the substrate to avoid heat losses by solid conduction into the substrate and to increase gaseous conduction. The sensitive elements exhibit a very high aspect ratio (length versus width) of 333 to perform high sensitivity enhanced by proper temperature uniformity. The oxide silicon micro-bridges provides the structure mechanical toughness over the fluid flow despite the wires length. The mechanical stress in this design is engineered using multilayer materials enabling a self compensating stress. Measurement wires are indeed 30 nm-Ni/40 nm-Pt multilayers reaching 130 nm height.

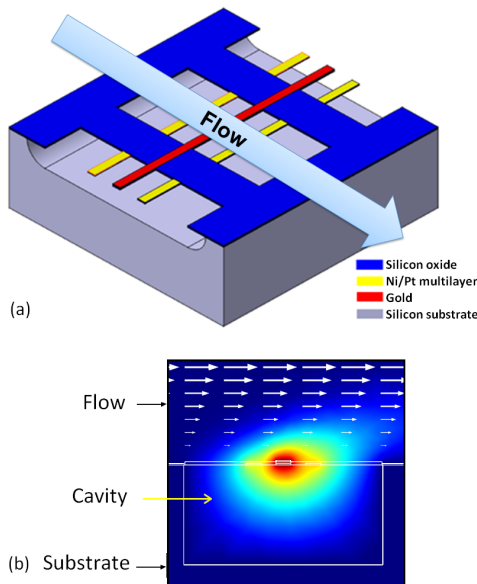


FIG. 1. Schema of the proposed sensor design (a) and working principle simulated on COMSOL Multiphysics (b)

The design allows sensor to operate in constant current mode or constant temperature mode. When the gold resistor is heated by electric current, the heat is transferred to the measurement wires and the surrounding fluid by conduction (Fig.1(b)). The changes in the heat distribution on the wire imply a temperature change at the wire level. Temperature variations cause

material resistivity change and consequently resistance variations in the measurement wires. Here, we chose Ni/Pt multilayer as it allows high resistance sensitivity to temperature as described below.

Fig.2 shows the micro-machining process performed on a 3 inches (100) silicon wafer allowing the fabrication of about 140 sensors.

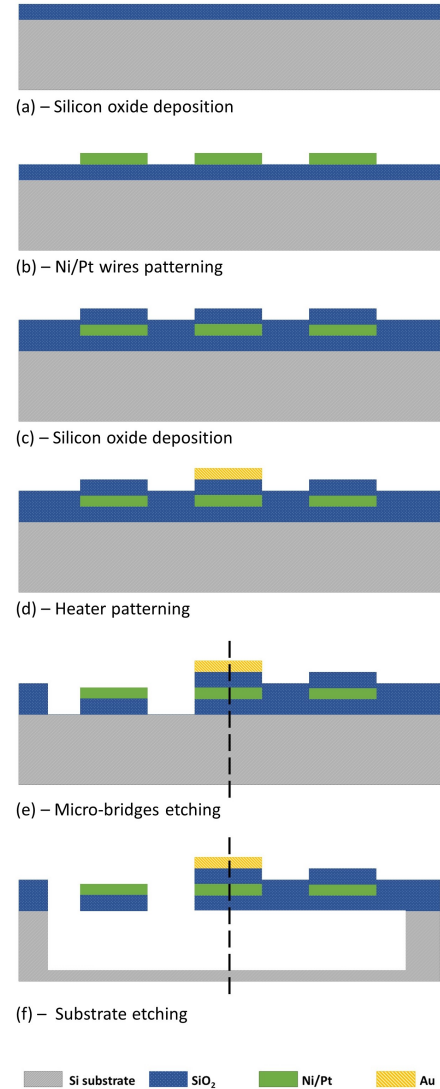


FIG. 2. Micro-machining process

First, 300 nm of silicon oxide (SiO_2) were deposited using Plasma Enhanced Chemical Vapor Deposition (PECVD). Measurement wires were then patterned using photo-lithography techniques and Ni/Pt multi-layer was deposited by evaporation. The metal was then removed using lift-off techniques to precisely define the wires. Another layer of SiO_2 was deposited using Low Pressure Chemical Vapor Deposition (LPCVD). The heater was then patterned using the same techniques as for the wires:

photo-lithography, metalization by evaporation and lift-off. The next step was the micro-bridges etch using Reactive Ion Etching (RIE) technique with CF_4 and ChF_3 plasma gas. On the corresponding picture (e) from Fig.2, two view are shown: the left one is the cross-view where there is no bridge and the right one is the view of the silicon oxide bridge. After the micro-bridges etching, the large contacts were defined and patterned (this step is not shown in Fig.2). The wafer was then cut to separate all the sensors. Finally each sensor was etched using XeF_2 plasma to separate the wires and the bridges from the substrate (Fig.2(f)) by isotropic etching.

Fig.3(a) and (b) are Scanning Electron Microscopy (SEM) pictures of our manufactured micro-sensor: Fig.3(a) shows the complete structure with the micro-bridges supporting the wires and Fig.3(b) is a zoom on the central elements, allowing to distinguish the heater from the measurement wire.

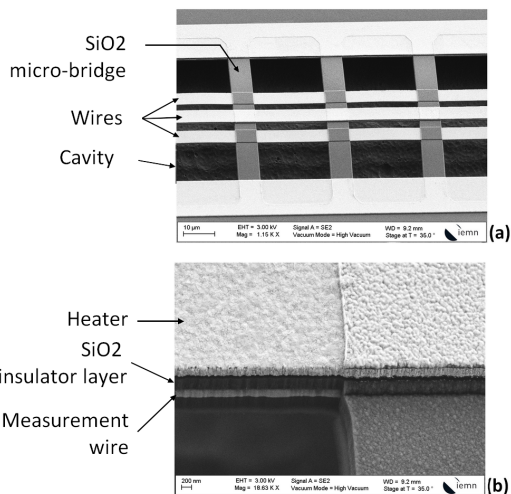


FIG. 3. SEM picture of the realized hot-wire sensor: general view (a) zoom on the central wire (b)

Then, we experimented both electrical and thermal characterizations of the sensor, without fluid flow. First we experimentally determined the Temperature Coefficient of Resistance (TCR) provided by the Ni/Pt multilayer. The TCR is a material characteristic, defined by $TCR = \Delta R / (\Delta T \cdot R_0)$ where R_0 is the resistance of reference at $25^\circ C$, ΔR the resistance variation and ΔT the temperature variation. We used a hot plate and a probe station for the measurements. The resistance variations with temperature exhibits a linear behavior between $20^\circ C$ and $70^\circ C$ resulting in a TCR of about 2380 ± 70 ppm/ $^\circ C$, with TCR dispersion measured across the 3 inches diameter wafer. Afterwards, the electrical temperature rise coefficient was measured. It represents the heating ability of the wires when the heater is traversed by an electric current going from 0 to 7 mA, and then provides information on the thermal insulation quality. The measurement set up

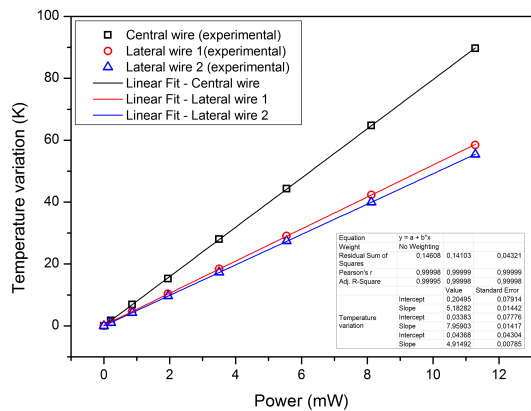


FIG. 4. Electrical characterization of the sensor for both central and lateral wires and comparison with numerical results

uses a Keithley 2400 source-meter and a probe station. Experimentally the temperature rise coefficient reaches 7.8 ± 0.9 K/mW for the central measurement wire and 5.0 ± 0.8 K/mW for lateral wires.

Finally, we characterized the sensor response to the fluid flow in a turbulent boundary layer wind tunnel located at the ONERA Lille center (Fig.5(a)). This 30 cm x 30 cm test section wind tunnel operates with velocities going from 0 m/s to about 40 m/s. The sensor mounted flush to the wall (Fig.5(b)) and the fluid velocity at the center of the test section is measured by a Dantec hot-wire probe.

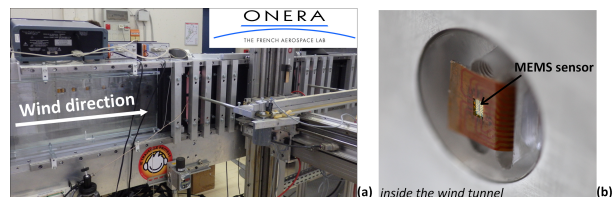


FIG. 5. (a) Turbulent boundary layer wind tunnel in ONERA Lille (b) MEMS Sensor mounted on the wall

We characterized the sensor evaluating resistance variation with the flow velocity at the center of the wind tunnel. We performed the experiments using the sensor in constant current mode, with 7 mA heating current, corresponding to about 11 mW. Results in (Fig.6) show resistance variation ΔR with flow velocity as $\Delta R = R(0 \text{ m/s}) - R(x \text{ m/s})$ for both central and lateral wires. As the wires are placed perpendicular to the flow lateral wires are distinguished as upstream and downstream the flow. Error bars represent the measure error which is not only due to the sensor noise but also to the wind tunnel flow velocity fluctuations.

The two lateral wires share electrical and thermal characteristics, so the difference of resistance variation present here, when the flow velocity is high enough, is

only due to the flow direction. The wire upstream the flow is more cooled than the wire upstream the flow.

As the resistance variations present a square-root behavior with the flow velocity, the sensor exhibits a sensitivity of about $0.06 \text{ \%}/\sqrt{m/s}$ for the central wire and the lateral upstream wire.

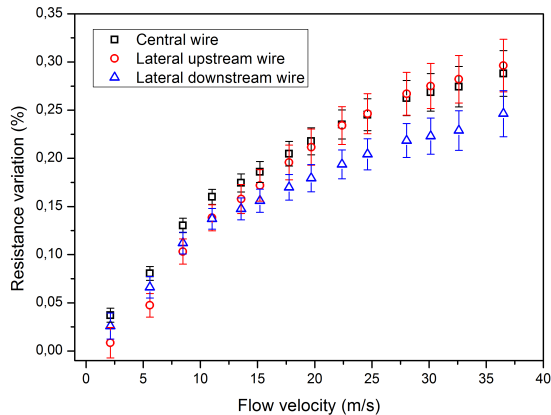


FIG. 6. Resistance variation at the tunnel wall versus flow velocity at the center for both central and lateral wires

Flow direction measurements were performed using the resistance difference between the two lateral wires. The aim in this experiment is to detect flow separation as the velocity field near the wall is reversed for a separated flow. The sensor setup in the wind tunnel enable to rotate the sensor from 0° to 180° . Measurement results are shown in Fig.7 and present the variation of the difference of resistance between the two lateral wires. The reference is taken for 90° when the

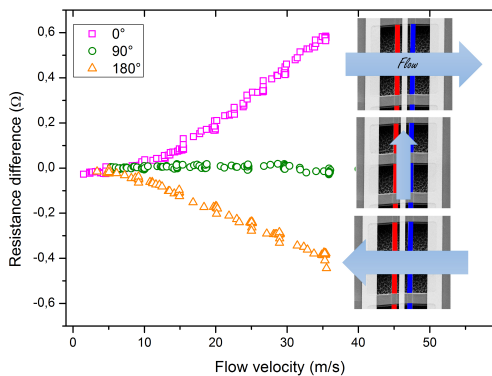


FIG. 7. Resistance variation of the difference of resistance between the two lateral wires at the tunnel wall versus flow velocity for different flow directions: 0° , 90° and 180°

sensor wires are parallel to the flow and thus the lateral resistances are equal. At 0° and 180° , the sensor wires are perpendicular to the flow, but at 180° the two lateral wires position is inverted compared to 0° .

In conclusion, we demonstrated an efficient and high sensitive high ratio hot wire based thermal MEMS sensor, presenting in this letter design, fabrication process, electro-thermal characterizations and wind tunnel experiments results. As a compromise between conventional hot-wires and hot-films sensors and taking advantages from both structures, the design consists in free hot-wires supported by silicon oxide micro-bridges. The sensor experiences high sensitivity to the near wall flows as well as low power consumption. The fabrication using micro-machining techniques allows low cost and high volume production and possibility of on-chip integration.

This work is financially supported by the French National Research Agency (ANR) in the frame of the ANR ASTRID CAMELOTT project. The authors also thank RENATECH the French national nanofabrication network.

- ¹L. Jacquin, *Aerospace Lab Journal* **01**, 01 (2009).
- ²L. Lofdahl and M. Gad-El-Hak, *Measurement Science and Technology* **10**, 665 (1999).
- ³V. Chandrasekharan, J. Sells, J. Meloy, D. P. Arnold, and M. Sheplak, *Journal of Microelectromechanical Systems* **20**, 622 (2011).
- ⁴P. Chen, Y. Zhao, and Y. Li, in *9th IEEE International Conference on Nano/Micro Engineered and Molecular Systems (NEMS)* (IEEE, 2014) pp. 350–353.
- ⁵T. von Papen, U. Buder, H. D. Ngo, and E. Obermeier, *Sensors and Actuators A: Physical* **113**, 151–155 (2004).
- ⁶U. K. Ayaz, T. Ioppolo, and M. V. tgen, in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition AIAA 2011-337 4 - 7 January 2011, Orlando, Florida* (2011).
- ⁷S. Große and W. Schrder, *AIAA Journal* **47**, 314–321 (2009).
- ⁸E. Vereshchagina, R. Tiggelaar, R. Sanders, R. Wolters, and J. Gardeniers, *Sensors and Actuators B: Chemical* **206**, 772–787 (2015).
- ⁹Y. Zhu, M. Qin, J. Huang, Z. Yi, and Q.-A. Huang, *IEEE Sensors Journal* **16**, 4300–4308 (2016).
- ¹⁰*Electronic Components and Technology Conference (ECTC), 2015 IEEE 65th* (IEEE, 2015).
- ¹¹J. Miao, T. Leu, J. Yu, J. Tu, C. Wang, V. Lebiga, D. Mironov, A. Pak, V. Zinovyev, and K. Chung, “Mems thermal film sensors for unsteady flow measurement,” *Sensors and Actuators A: Physical* **235**, 1–13 (2015).
- ¹²T. Leu, J. Yu, J. Miao, and S. Chen, *Experimental Thermal and Fluid Science* **77**, 167–178 (2016).
- ¹³A. Talbi, L. Gimeno, J.-C. Gerbedoen, R. Viard, A. Soltani, V. Mortet, V. Preobrazhensky, A. Merlen, and P. Pernod, *Journal of Micromechanics and Microengineering* **25** (2015).
- ¹⁴P. Pernod, L. Gimeno-Monge, A. Talbi, A. Merlen, R. Viard, V. Mortet, A. Soltani, and V. Preobazhensky, “Hot-wire sensor of submillimeter size and associated method of production,” (2011), fR2958754 (A1) 2011-10-14 WO2011128828 (A1) 2011-10-20 FR2958754 (B1) 2012-10-26 EP2561369 (A1) 2013-02-27 US2013125644 (A1) 2013-05-23 JP2013527436 (A) 2013-06-27 US8978462 (B2) 2015-03-17 EP2561369 (B1) 2015-04-01 DK2561369 (T3) 2015-07-06 JP5770828 (B2) 2015-08-26.
- ¹⁵Y. Fan, G. Arwatz, T. W. Van Buren, D. E. Hoffman, and M. Hultmark, *Experiments in Fluids* **56** (2015).
- ¹⁶R. Viard, A. Talbi, A. Merlen, P. Pernod, C. Frankiewicz, J.-C. Gerbedoen, and V. Preobrazhensky, *Journal of Micromechanics and Microengineering* **23** (2013).
- ¹⁷R. Viard, A. Talbi, P. Pernod, A. Merlen, and V. Preobrazhensky, “Miniaturised Sensor Comprising A Heating Element, And

Associated Production Method,” (2013), fR2977886 (A1) 2013-01-18 WO2013008203 (A2) 2013-01-17 WO2013008203 (A3) 2013-03-07 CN103717526 (A) 2014-04-09 EP2731908 (A2) 2014-05-21 US2014157887 (A1) 2014-06-12 EP2731908 (B1) 2015-09-09 DK2731908 (T3) 2015-12-21.

¹⁸T. Charbert, *Controle experimental en boucle fermee du decollement sur un volet.*, PhD dissertation, Universit Pierre et Marie Curie - Paris VI (2014).

¹⁹N. André, B. Rue, G. Scheen, D. Flandre, L. A. Francis, and J.-P. Raskin, *Sensors and Actuators A: Physical* **206**, 67–74 (2014).