Hybrid-Mounted Micromachined Aluminum Hotwires for Wall Shear-Stress Measurements

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***Abstract*—In this paper, we present a micromachined metal hotwire anemometer sensor for use in wall shear-stress measurements. We describe its design and fabrication. A novel hybrid assembly method has been developed to make it possible to measure close to the surface without contacting leads interfering with the flow. Experimental results illustrate the behavior and characteristics of this sensor. [0980]**

***Index Terms*—Aluminum, anemometers, assembly, hotwire, microassembly, microsensors, wall shear stress.**

I. Introduction

WALL shear stress is an important fundamental parameter in characterizing and understanding flow near a wall. Detailed information on the flow in the vicinity of the wall is of particular interest for various types of flow and heat transfer predictions and of basic importance for turbulence modeling. The time-averaged value of the wall shear stress can be accurately determined by a number of methods. The time-resolved part however, is more difficult to measure, since it requires small sensors in the order of 100 μm with a temporal resolution of up to 10 kHz [1]. MEMS is therefore an obvious choice. Several solutions within the field have been presented. [1]–[6] Their basic principles can be divided into two groups [2], [6]: direct techniques, such as floating-element devices, and indirect techniques, such as hotwires and hotfilms. [2]–[5], [7] Miniaturization though, is only one of the issues that needs to be addressed in order to be able to make accurate wall shear-stress measurements. Mechanical interference with the measured flow must be avoided. Integrating the wall shear-stress sensor in the wall instead of having a separate device, reduces the interference. But still, for all types of wall shear-stress sensors, the wire contacting can interfere with the measured flow. Two solutions are possible: either the leads can be made long and placed far downstream [5], or they can be placed completely outside of the flow by having them go into the wall.

In particular for the indirect techniques, thermal cross talk with the surface is an important aspect. More specifically, the surface near the sensor acts as a heat sink and affects the measurement. Those solutions addressing this problem, have concentrated on complete thermal insulation of the sensing device from the surface, either by air or vacuum. [4] This reduces the cross talk, but can never completely eliminate it, since one always needs a connection to the surface due to the electrical leads to the sensor, which causes the vicinity of the sensor to heat up to a certain extent anyway

When it comes to measuring the wall shear stress indirectly, measuring the velocity of the fluid is a good option. This is made possible by two relationships. On one hand, the wall shear stress τ is directly proportional to the shear rate $\partial V_{||}/\partial n$ [8], where $V_{||}$ is the streamwise fluid velocity and n is the direction normal to the surface. On the other hand, the velocity profile of a flow is linear within the viscous sublayer, which extends a short distance from the surface. This implies that the fluid velocity at a fixed distance from the surface within the viscous sublayer is linearly dependent of the shear stress. Therefore, if one wishes to measure the shear stress by measuring the velocity of the flow, the highest sensitivity can be achieved by measuring as far from the surface as possible, yet staying within the viscous sublayer. An approved method of measuring fluid flow at a discrete point in space is to use a hotwire anemometer. Conventionally fabricated metal hotwires are commonly used to measure airflow speeds with high spatial and temporal resolution for use in windtunnel applications. The underlying principle of a hotwire anemometer is that the heat transfer from a heated surface of the wire only depends on the flow characteristics around the wire. This implies that by heating a wire and measuring the supplied electrical power, one can find a measure for the velocity of the airflow over this wire. The most common implementation for making use of this principle is called constant temperature anemometry (CTA). Here the wire is kept at a constant temperature by a feedback circuit. The amount of feedback needed to maintain constant temperature is dependent of the airflow. The advantage of this method is that the time constant of the entire system is governed by the bandwidth of the measuring electronics and not by the thermal mass of the wire. This increases the measurable frequency range by up to two orders of

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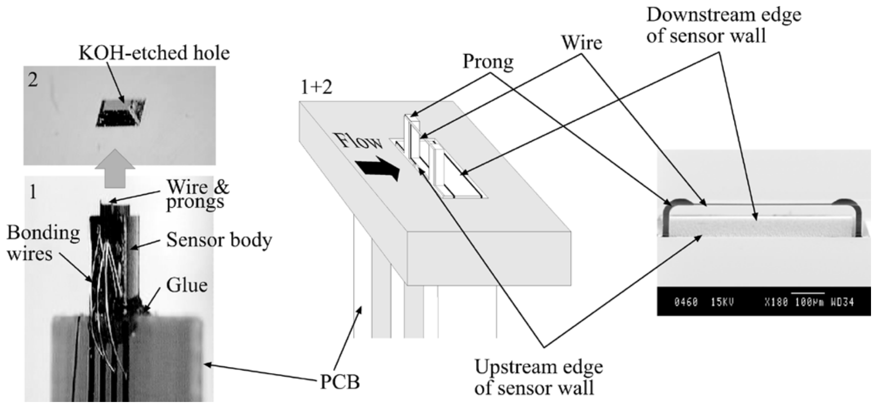

Fig. 1. Hybrid assembly (a) The sensing chip glued and wire bonded to the tip of a PCB is inserted in the KOH-etched hole in the holding chip. (b) After insertion the "sensor wall" is in-plane with the holding chip wall. (c) SEM micrograph of the front of an assembled sensor.

magnitude as compared to constant current or constant voltage anemometry [9].

Since their invention over a century ago, hotwires have not lost their popularity. The upcoming of MEMS brought along the promise of being able to make them even smaller, providing higher spatial and temporal resolution [4], [10]–[15]. An advantage of MEMS hotwires over conventional hotwires, even when they are at similar dimensions, is that their dimensions are more reproducible. Yet, MEMS-based hotwires are far from perfection, many of them use for example polysilicon instead of metal for the wire, requiring specific electronics because of their high resistance [2].

We will present a hotwire sensor intended for measuring the wall shear stress by measuring the velocity of a flow very close to the surface. The sensor is not flush with the surface and the contacting is done outside of the flow. The resistance of the aluminum hotwire is of the same order of magnitude as conventional hotwires, allowing it to be used with commercially available constant temperature anemometry systems. Design parameters and fabrication issues will be discussed and experimental results demonstrate the performance of the device.

II. Design Considerations

The present sensors are developed especially to measure fluctuations of the wall shear stress. In order for the hotwire sensors to work as wall shear-stress sensors in the turbulent flows, they need to be in the viscous sublayer, where the velocity profile is linear. The thickness of this viscous sublayer can be estimated as $5\nu\sqrt{\rho/\tau}$, where ν is the kinematic viscosity of air ($1.460 \cdot 10^{-5}\ \mathrm{m^2/s}$), ρ the air density ($1.225\ \mathrm{kg/m^3}$) and τ the wall shear stress. The range of shear stress we are interested in is 0 to 2.5 Pa. At 2.5 Pa, the viscous sublayer extends about 50 $\mu\mathrm{m}$ from the surface. This implies that the hotwire can be at the most 50 $\mu\mathrm{m}$ from the surface in order to be able to measure a shear stress as high as 2.5 Pa. If one only wishes to measure shear stresses up to 0.7 Pa, the hotwire can be placed at 100 $\mu\mathrm{m}$ from the surface, which results in a higher sensitivity.

To provide sufficient spatial resolution in the turbulent flow, the probe length should be as small as possible. The maximum recommended probe length is 20 to 25 times $\nu\sqrt{\rho/\tau}$. Furthermore, to avoid that the sensor interferes mechanically with the flow, it is recommended in conventional hotwire anemometry [9] to have a prong diameter of about one tenth of the prong spacing to minimize possible effects of flow modification. For conventional hand-made wall-mounted hotwires, this is often a problem, while as for MEMS hotwires this principle is easily obeyed. Concerning the electrical contacting, placing the contacts downstream is the easiest solution to the issue of electrical connections to the hotwire. This however results in inefficient use of chip area, since the leads have to be long enough so as not to disturb the flow. Besides increasing the fabrication cost per device, the leads limit the flexibility for any combination with other sensors or actuators. However, by fabricating the leads through the surface instead, so that the contacts are outside of the flow reduces the footprint drastically. The disadvantage was that until now, this has been a comparatively complex process due to the difficulty of making wafer-through vias. A major disadvantage of conventional hotwires is that it is very hard to create arrays of them. The price of conventional multi-wire hotwires increases drastically when more than one wire is used, due to the difficulty of manually applying hotwires. It is with these considerations in mind that we came to a new design that combines the advantages of both methods. Our solution, the hybrid assembly, is illustrated in Fig. 1. Since our device is placed through a hole in a covering chip, the leads only have to be a bit longer than the thickness of the covering chip. The fact that the patterned surface of the chip is perpendicular to the wall provides us with an extra degree of freedom in the design of the supporting structure and consequently a high precision in the choice of the wire-to-wall distances. The possibility of placing several hotwires on one device chip, creating an array of hotwires is as easy as creating a device which only has a single one.

We have chosen aluminum as our hotwire material. This results in a device that stands in contrast with most other MEMS hotwire anemometers and allows us to use it in conjunction with standard CTA measuring equipment. Since aluminum is hard to weld or solder to the prongs, it is not used in conventional hotwires. Within the electronics industry though, aluminum processing is however a well-established technology and therefore quite straightforward. Data shows that the performance of aluminum wires is as good as conventional hotwires both in terms

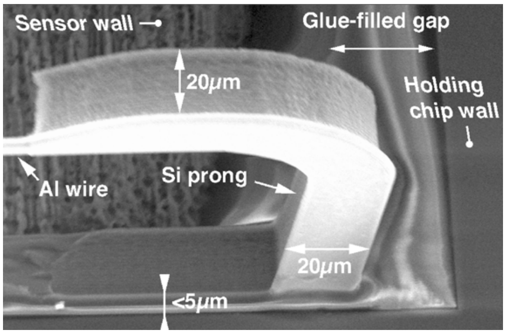

Fig. 2. SEM micrograph showing a close-up of a prong.

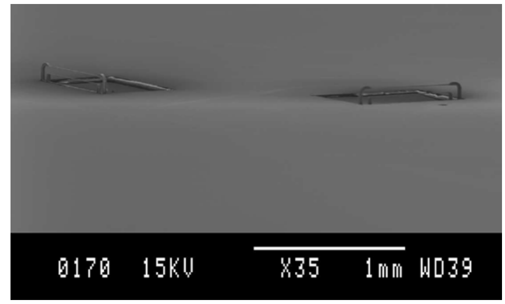

Fig. 3. Two 2-wire sensors (600 μm long) in XY configuration.

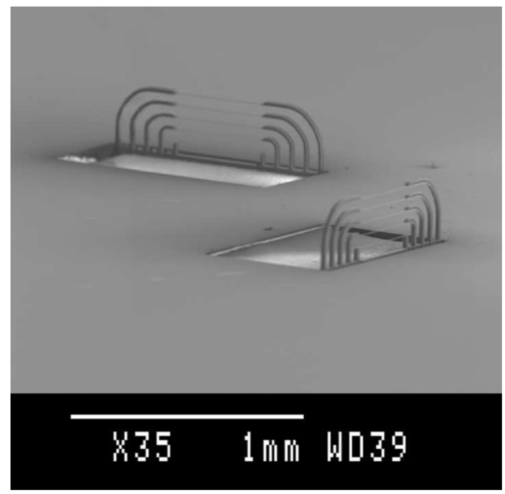

Fig. 4. Two 5-wire sensors (400 μm long) in XY configuration.

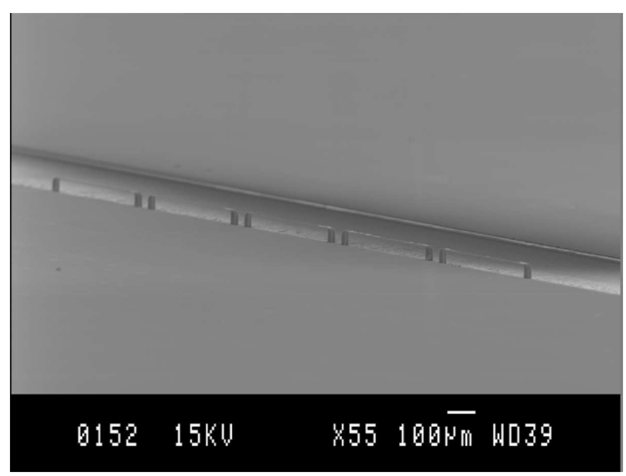

Fig. 5. Sensor chip with five wires (400 μm long) next to each other.

of the temperature coefficient of resistivity (0.0038 K^{-1} against 0.0036 K^{-1} for tungsten) and in terms of thermal conductivity (235 $\mathrm{W/m \cdot K}$ against 170 $\mathrm{W/m \cdot K}$).

III. Design

We have designed, fabricated and tested several versions. The cross-sectional dimensions of the wires span from 1 μm× 2 μm to 3 μm× 2 μm. The lengths fabricated were 200 μm, 400 μm and 600 μm. The prongs held the devices at distances from the wall ranging from 50 μm to 250 μm. At the base, their cross section was 20 μm× 20 μm, as shown in Fig. 2. We have fabricated 2 and 5-wire vertical arrays on single chips and combined them to form 4 and 10-wire arrays, as shown in Figs. 3 and 4. We have also fabricated 5-wire horizontal arrays, "rakes", as illustrated in Fig. 5. The packaged device consists of one or more sensor chips inserted in a cover chip with a tube attached to protect the PCB and facilitate handling, as illustrated in Fig. 1. For multi-device setups as shown in Fig. 4 no tube was used, but instead packaging epoxy was used to fix the two orthogonal PCB's to each other and so provide easy handling. The cover chip is a 20 mm × 20 mm square diced out of a 300 μm thick wafer with a KOH-etched hole. The cover chip hole allows for a gap of less than 10 μm between the sensor chip and the cover chip. E.g. for a 580 μm× 565 μm chip (holding up a 400 μm wire), this hole is 600 μm× 585 μm. The most important factors for this measurement technique are the accuracy of the wire placement parallel to the wall and its position in relation to the wall. We were able to achieve tolerances of about 3 μm for these parameters.

The sensor chip is inserted and fixated with a maximum tolerance of 10 μm within the plane of the cover chip. This is an order of magnitude smaller than the required spatial resolution. Several design details ease the insertion and enhance the smoothness of the surface: The sloping walls of the insertion hole facilitate hotwire insertion without compromising its size on the front. The low-viscosity glue is subject to capillary forces which cause it to bridge the hole between the sensor chip and the cover chip, evening out the surface even more. The prongs are curved inward to provide a margin of movement while the chip is being positioned in the cover chip hole. The fact that the outer dimensions of the cover chip are defined by dicing, keeps the possibility of easily fitting the entire device to different measurement setups without changes in the process flow. The reason of designing a multi-wire hotwire is to increase the flexibility of the device. An analysis of the heat transfer characteristics of the sensor [16] shows that wires located too close to the wall have to trade in on their sensitivity due to the low velocity and the heat transfer to the wall via the air and through the supports. This causes them to start behaving very similar to conventional hotfilms. The wire distance from the wall therefore is a compromise between range and sensitivity, so it is an advantage to have a multi-wire sensor where the wires are at different distances from the wall to measure the wall shear stress in different ranges with improved accuracy. Close to the wall, the local velocities are smaller and the influence from the wall is larger, hence, for the same wall shear stress, a wire located closer to the wall, will

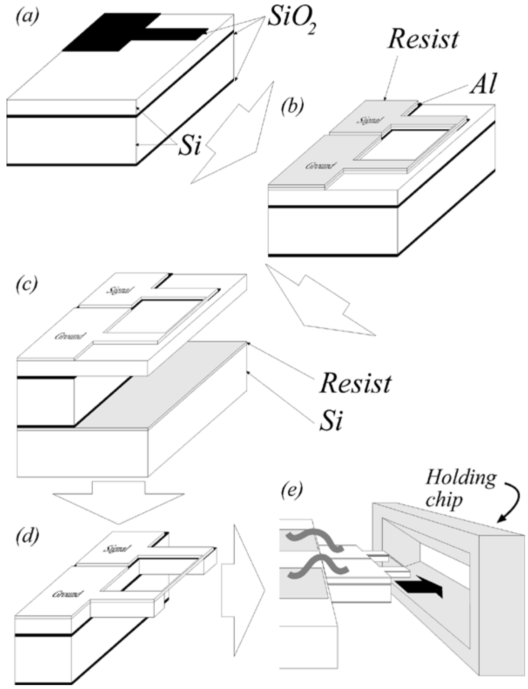

Fig. 6. Process flow.

give a smaller output signal. By inserting two sensors at an angle to each other, the unknown flow angles of the instantaneous velocity vector can be resolved.

IV. Fabrication

The total fabrication can be divided into two parts; a MEMS part where the sensor and cover chips are fabricated, and a hybrid part, where the sensor chip is inserted into the cover chip:

A. MEMS Fabrication

A bulk micromachining process is used to form the hotwire probe. The fabrication is performed on a 100 mm diameter (100) Silicon-on-insulator (SOI) wafer consisting of a 20 μm thick silicon layer on a 1.5 μm thick SiO_2 layer, on top of the 525 μm thick silicon substrate. Fig. 6 outlines the sensor fabrication steps described below.

a) On both sides of the wafer a 2 μm thick thermal oxide layer is grown. After being thinned down to a thickness of 200 nm, the front side oxide is photolithographically patterned and dry etched down to the top silicon layer to define areas where the aluminum ground leads are isolated from the silicon substrate. Then the resist is stripped in an oxygen plasma.

b) A 2 μm aluminum layer is sputtered on the wafer surface and patterned with the second mask defining the wires and leads. Reactive ion etching (RIE) is used to structure the patterned aluminum layer. Due to the high anisotropy of the etch, the cross section of the wires is rectangular.

c) To protect the front side of the structures during back side processing, resist is spun on the front side. The SiO_2 on the back side of the wafer is photolithographically patterned with a third mask using a back side mask aligner. The SiO_2 is etched with buffered HF. Using the oxide and the resist as a mask, the 525 μm thick silicon substrate is etched anisotropically in an inductively coupled plasma (ICP) etch (deep reactive ion etching, DRIE). The buried oxide layer of the SOI wafer serves as an etch stop layer. The 1.5 μm thick buried oxide is then etched with RIE and buffered HF. The RIE was performed to remove most of the oxide, since a pure BHF would cause the buried oxide to crack. The BHF was needed for removing the remaining oxide near the edges. To continue processing on the front side, the protecting resist is removed in an oxygen plasma. To support the now fragile wafer, a silicon wafer is glued to the device wafer's back side using resist as an adhesive.

d) The prongs are formed in an ICP silicon etch using the aluminum and oxide structure as a mask. This results in 20 μm thick prongs sticking out of the body of the sensor. To free the wire from the silicon underneath, a 3 μm isotropic silicon etch is performed in the ICP.

e) Finally the devices can be separated from each other by breaking the fragile wafer carefully along cleaving lines provided on the back side. The sensors are then glued to PCB's and wire-bonded. A 300 μm thick (100) silicon wafer was used for the fabrication of the sensor holding chips. The holes in these wafers are etched in a KOH bath

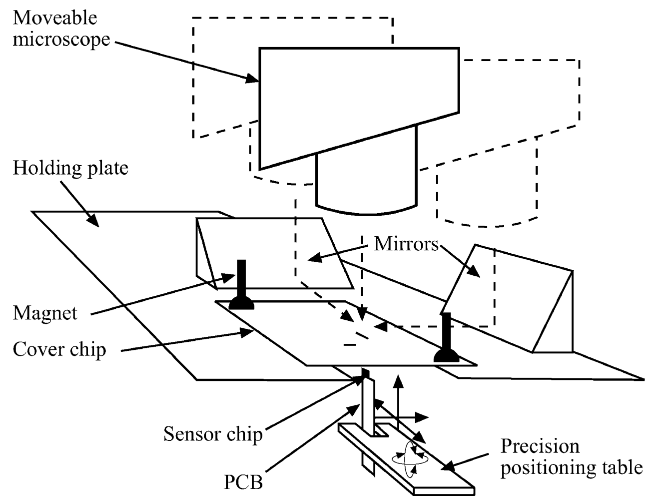

Fig. 7. Assembly setup.

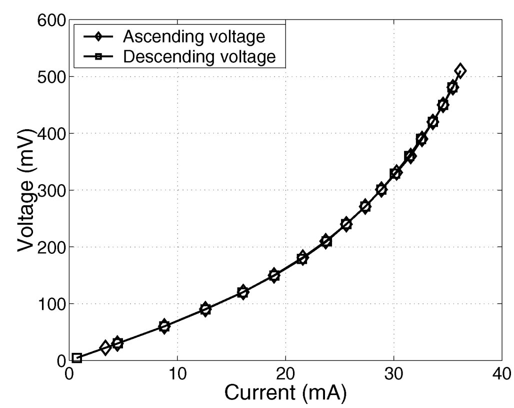

Fig. 8. Voltage-current measurement of a 1 $\mu\text{m} \times 3$ $\mu\text{m} \times 600$ μm long hotwire. Self-heating due to ohmic losses cause the line to curve upward.

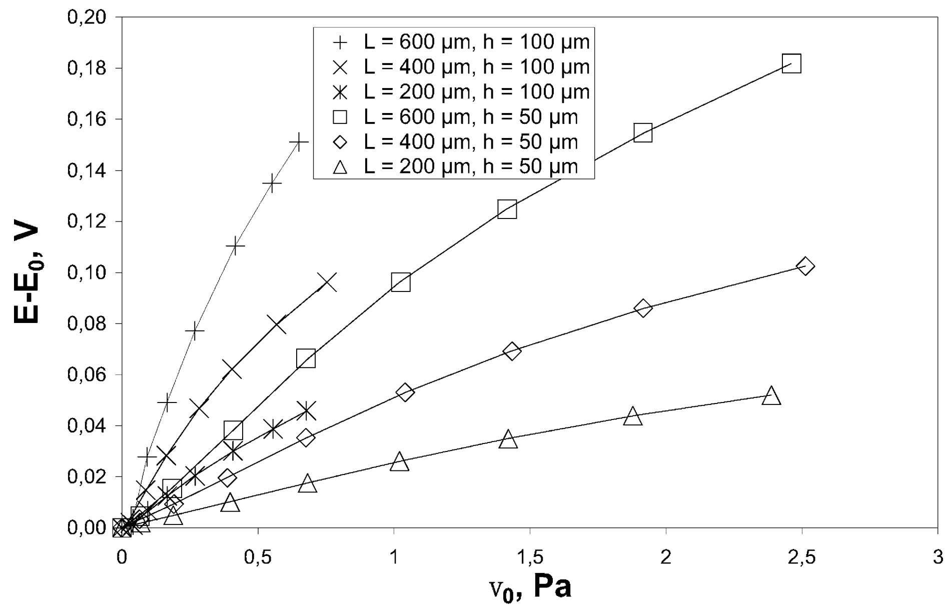

Fig. 9. Calibration curves of 6 types of hotwires.

using a 2 μm thick oxide layer as a mask. The fact that the holes are slanted facilitates the assembly of the sensor in the holding wafer.

B. Hybrid Assembly and Installation

A positioning table was built for assembly of the sensor. The table had three translational and three rotational degrees of freedom. The glue used for fixation was a UV-hardening epoxy, EpoTek OG-154. By mounting mirrors at two directions, face-on and from the side, as shown in Fig. 7, it was possible to use one microscope to verify that the wires were completely parallel and the prongs completely vertical to the cover chip. Fig. 2 shows a SEM micrograph close-up of one prong of an inserted device. Note the glue pulled up by capillary forces, bridging the gap between the sensor and the cover chip. The glue compensated for wafer thickness tolerances which caused the gap for some wafers to be up to 20 μm, therefore allowing the device after fixation to still comply with the maximum step tolerance of 10 μm. An advantage of this glue was that it could be hardened instantly, permitting a larger throughput of assembled devices. Furthermore, the mirror setup enabled control of the device's position both before and after hardening. Finally, a tube is glued to the back side and filled up with filling epoxy for easier handling. The entire setup is placed in a plexiglass chuck which, in turn, is placed in the wall of the wind tunnel.

V. Performance

Several measurements have been done to validate the performance of our sensor as a hotwire. Fig. 8 shows the current-voltage characteristic of a 1 μm$\times$ 3 μm cross-section wire with a length of 600 μm. As expected, the graph clearly curves upwards because of the wire resistance increase due to the self-heating of the wire. This self-heating is important to be able to effectively heat up the wire to its operating temperature.

To verify the performance of the sensor in a windtunnel environment, calibration of the hotwires has been performed. Fig. 9 shows the calibration curves for 200, 400 and 600 μm wires at 50 and 100 μm from the surface. The cross section of the wires was 2 μm$\times$ 1 μm, 2 μm$\times$ 2 μm and 2 μm$\times$ 3 μm, respectively, such that the resistance of the wires was the same and the ratio of wire length to wire thickness was 200 for all of them. As expected, wires with larger dimensions (length and circumference) provide higher sensitivity than wires with smaller dimensions, and wires farther from the surface provide larger output since they measure a higher velocity than those closer to it (at constant wall shear stress). The wires at 100 μm from the surface were calibrated only up to about 0.7 Pa, since the viscous boundary layer at higher wall shear stresses is thinner than 100 μm. The wires at 50 μm, for the same reason, were calibrated up to a wall shear stress of 2.5 Pa.

The sensitivity of the 400 μm wires was found to be in the range of 100 to 300 mV/Pa at an overheat of 1.5. This sensitivity is significantly higher than that of flush-mounted hot-films. [2], [4] Furthermore, the sensitivity of the wire at 100 μm from the wall is about two to three times as high as that for the wire at 50 μm from the wall, illustrating the advantage of using multi-wire devices. The design methodology and requirements are discussed in more detail in [16], where also the characteristics of the present hotwire sensors are evaluated. In this work [16], also the heat transfer and thermal cross talk are estimated numerically, the necessary calibrations are discussed, and some windtunnel measurements are reported. The calibration of the current microsensors in a boundary layer was performed and they are found to have good steady-state characteristics. In addition, the developed sensors were used for preliminary studies of transitional phenomena and turbulence, and the sensors were found to have a good time-dependent response as well. The sensor was used to measure small-amplitude oscillations during the transition from laminar to turbulent flow and detected weak eigen disturbances of the boundary layer. To our knowledge, this is the first experiment where a MEMS-based sensor was able to measure this. This allows the sensors to be used for flow control purposes. Measurements in turbulent flow with the current sensors are described in [17], where the wall shear-stress fluctuations in a turbulent boundary layer of a flat plate are measured.

VI. Conclusion

We have successfully designed, fabricated and characterized a micromachined hotwire anemometer for wall shear-stress measurements. The dimensions of the wire, which go down to $1\ \mu\text{m}\times 2\ \mu\text{m}\times 200\ \mu\text{m}$, are small enough to achieve the required spatial resolution for the described application. Sensors with multiple wires were produced, both in parallel with each other and orthogonal to each other. The use of the aluminum wire allows the device to be used with existing CTA equipment, thereby providing the required temporal resolution. The hybrid assembly method did not introduce any steps over $10\ \mu\text{m}$ and permits easy through-wafer contacting. It therefore does not cause interference with the flow. We have confirmed the functionality of the sensor as a hotwire with characterization measurements and windtunnel calibrations. Experiments in the windtunnel have verified the feasibility of the hotwire anemometer for wall shear-stress measurements.

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Valery Chernoray, photograph and biography not available at time of publication.

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In 1984, he was appointed Docent (the highest academic degree in Sweden) and held positions as Researcher and Associate Professor. In 1999, he was appointed Professor of Fluid Dynamics at Chalmers University of Technology. He has been teaching undergraduate courses in Thermodynamics, Basic and Advanced Fluid Mechanics. He has taught graduate courses in Fluid Dynamics, Turbulence and Experimental Fluid Dynamics. He has supervised more than 125 M.Sc. theses, many of them in cooperation with industries. His current research topics are flow stability and transition, the use of MEMS technology in fluid dynamics with emphasize on sensors and flow control, experimental fluid dynamics. During the last years professor Löfdahl has worked in the field of vehicle aerodynamics and developed experimental equipment for force measurements on vehicles. The publication list includes more than 100 papers in well-recognized journals, books and proceedings. He has delivered a number of invited lectures and papers. He is involved in referee tasks for more than ten international journals.

Göran Stemme (M'98) received the M.Sc. degree in electrical engineering in 1981 and the Ph.D. degree in solid-state electronics in 1987, both from the Chalmers University of Technology, Gothenburg, Sweden.

In 1981, he joined the Department of Solid State Electronics, Chalmers University of Technology, where, in 1990, he became an associate professor (Docent) heading the Silicon Sensor Research Group. In 1991, he was appointed Professor with The Royal Institute of Technology, Stockholm, Sweden, where he heads the Microsystem Technology Lab, Department of Signals, Sensors and Systems. His research is devoted to microsystem technology based on micromachining of silicon. He has published more than 100 research journal and conference papers and has been awarded eight patents.

Dr. Stemme was a member of the International Steering Committee of the Conference series IEEE Microelectromechanical Systems (MEMS) during 1995 and 2001, and was General Co-Chair of that conference in 1998. He is a member of the Editorial Board of the IEEE/ASME JOURNAL OF MICROELECTROMECHANICAL SYSTEMS and of the Royal Society of Chemistry journal *Lab On A Chip*. In 2001 he won, together with two colleagues, the final of Innovation Cup.