HYBRID MOUNTED MICROMACHINED ALUMINIUM HOT-WIRE FOR NEAR-WALL TURBULENCE MEASUREMENTS

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ABSTRACT

We present the first micromachined metal hot-wire anemometer sensor for use in near-wall turbulence measurements. To measure close to the surface without the circuitry interfering with the flow, a novel hybrid assembly of the sensor has been developed. We present the design, fabrication and characteristics of this sensor.

INTRODUCTION

To measure airflow speeds with high spatial and temporal resolution as needed in windtunnel applications, it is very common to use conventionally fabricated metal hot-wires.

The principle of operation of a hot-wire anemometer is based on the relationship between the cooling effect of an airflow and the temperature dependence of a wire's resistance. A wire is heated by an electrical current and is positioned in an airflow which cools the wire and thereby changes its resistance. By measuring the feedback current needed to keep the resistance of the wire constant, and thus the temperature constant, one can measure the speed of the airflow. This method is called constant temperature anemometry (CTA).

Hot-wires have been used for over a century and are still very popular. Since smaller wires provide higher spatial and temporal resolution, MEMS has been an evident advantage. [1-7] A drawback of MEMS-based hot-wires however, is that they most often use polysilicon wires and thus (due to their high resistance) need special electronics compared to standard metal hot-wires.

MEMS hot-wires lend themselves well to measurement of turbulent flows due to their small size and low time constant. However, a problem arises when one wants to measure close to a surface since flow interference and thermal cross talk with the surface make the measurements unreliable. Therefore, specialized hot-wires are needed for this application. The solution is to have the sensor attached to the wall, which can greatly reduce the flow interference. Two major difficulties need to be considered: 1) to control the inevitable thermal influence from the wall that occurs at the distances we are interested in (<250μm.) 2) to place the contact leads to the sensor outside of the measured flow. This can be done either by placing the contact leads far downstream, or by wafer-through vias.

In this paper we will present a novel hot-wire sensor, measuring the velocity at a very small distance from a surface. Aluminium is used as the wire material, allowing it to be used with standard CTA systems. The contacting is done from the back side of the surface so as not to impede the flow. We will describe all the factors taken into account during the design and fabrication and the experiments performed to verify its function.

DESIGN CONSIDERATIONS

The application area we are interested in is measuring the turbulent flow at low speeds (free stream velocity <20m/s) very near the surface of a wall (<250μm.) The scale of the smallest eddies to be resolved in turbulent flow for a complete analysis is of the order of 2-3 Kolmogorov lengths, which corresponds to about 2 to 3 times 100μm here. [8] This means that the wire length must be of the same order of magnitude. When measuring turbulent flow at such small dimensions, the sensing device must not interfere with the flow. The largest allowed sensing structure in the measured flow must be much smaller than the wire length, which in our case ranges from 200μm to 600μm.

When considering the electrical connections, placing them downstream results in easier fabrication. However it also brings two disadvantages. The first one is that the size of the sensor chip is drastically increased due to the length of the leads needed to not disturb the flow around the wire, thus increasing the production cost. The second disadvantage is that it leaves little flexibility in combining the sensor with other sensors or actuators because the leads get in the way. The alternative, having the contacts on the other side of the surface allows for a much smaller footprint but has until now been a fairly complicated procedure due to the challenge of making wafer-through vias.

In view of this, we decided to combine the advantages of both methods into a new one. Our solution, the hybrid assembly, is illustrated in Figure 1. By placing the device through a hole in the wall, we limit the minimum lead length to a bit more than the covering chip thickness, while having the leads outside of the flow. Having the patterned surface of the chip perpendicular to the wall provides us with a high precision and flexibility in terms of the choice of wire-to-wall distances.

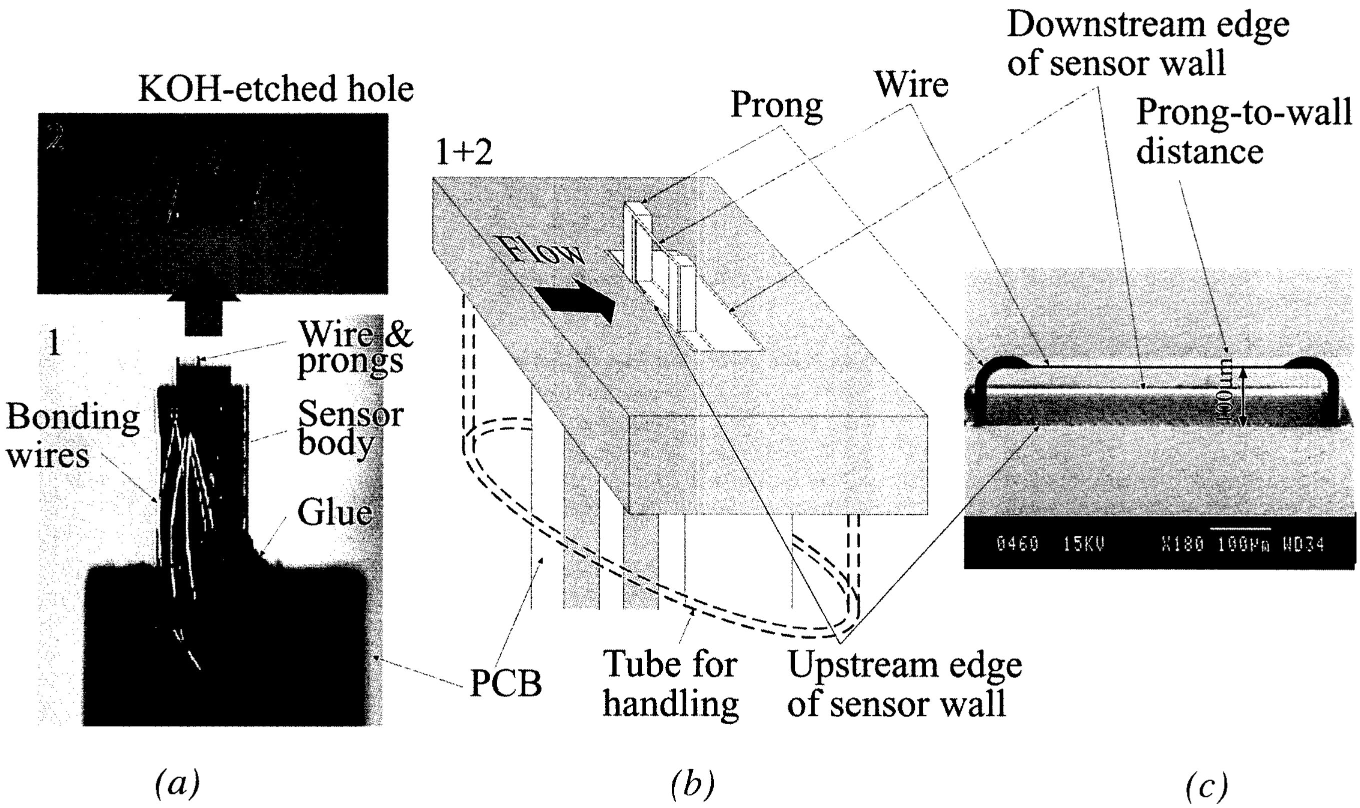

Figure 1: Hybrid assembly
Left: The sensing chip glued and wire bonded to the tip of a PCB is inserted in the KOH-etched hole in the holding chip.
Middle: After insertion the "sensor wall" is in-plane with the holding chip wall.
Right: SEM micrograph of the front of an assembled sensor.

Our selection of the hot-wire material is aluminium. This differs from most other MEMS hot-wire anemometers and enables us to use the sensor with standard CTA measuring equipment. Aluminium is not used for conventional hot-wires, because of the difficulty in welding or soldering it to the prongs. In micromachining, however, the processing of aluminium is fairly uncomplicated. Data shows that the performance of aluminium wires is as good as conventional hot-wires both in terms of the temperature coefficient of resistivity (0.0038 K^{-1} against 0.0036 K^{-1} for tungsten) and in terms of thermal conductivity (235 W/m·K against 170 W/m·K).

DESIGN

Several versions have been fabricated. The sizes of the fabricated hot-wires range from 1µm x 2µm x 200µm to 3µm x 2µm x 600µm. The wire is held up at distances ranging from 50µm to 250µm from the surface by a pair of prongs with a cross section of 20µm x 20µm. (See Figure 1c & Figure 3.) The sensor chip is attached and wire-bonded to a PCB. This is then positioned in a KOH-etched hole in a cover chip. The size of the hole is such that there is less that 5µm of space between the sensor chip and the cover chip. The cover chip is 20mm x 20mm in size and 300µm thick. These outer dimensions were designed for our measurement setup, but we can easily vary the outer dimensions of the cover chip by dicing it differently. A tube glued to the back side of the cover chip which filled up with filling epoxy facilitates handling. (See Figure 1b.) The entire setup is placed in a plexiglass chuck which, in turn, is placed in the wall of the wind tunnel.

The maximum step introduced in the system besides the prongs is 10µm. The gap between the sensor chip and holding chip is bridged by the glue, which is pulled to the correct position by capillary forces. The prongs are curved inwards to ease insertion, i.e. they provide a margin for movement when the chip is being positioned. The rhomboidal shaped hole in the holding chip gives extra maneuvering space without compromising the hole size on the front.

FABRICATION

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

1. MEMS fabrication

A bulk micromachining process is used to form the hot-wire probe. The fabrication is performed on a 100mm diameter (100) Silicon-on-insulator (SOI) wafer consisting of a 20µm thick silicon layer on a buried 1.5µm thick SiO_2 layer, on top of the 525µm thick silicon substrate. Figure 2 outlines the sensor fabrication steps described below.

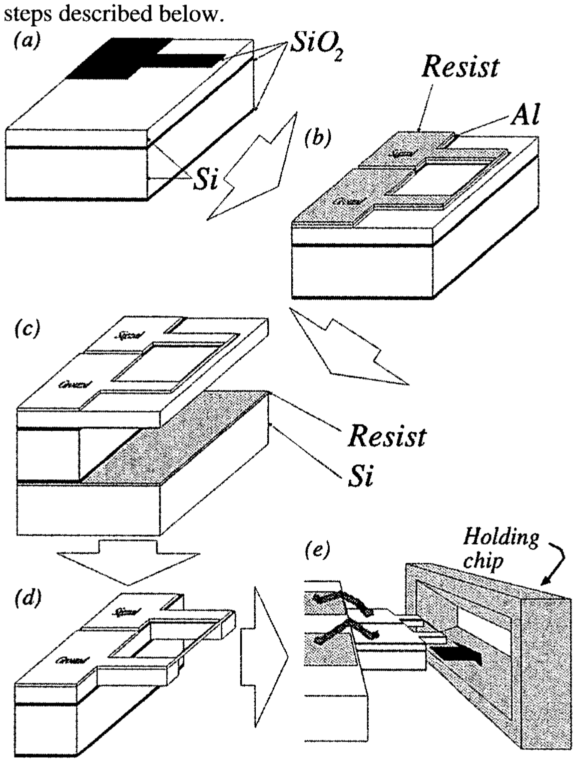

Figure 2: Process flow

(a) On both sides of the wafer a 2µm thick thermal oxide layer is grown. After being thinned down to a thickness of 2000Å, the front side oxide is photolithographically patterned and dry etched down to the top silicon layer to define areas where the aluminium ground leads are isolated from the silicon substrate. Then the resist is stripped in an oxygen plasma.

(b) A 2µm aluminium 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 aluminium 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 525µm thick silicon substrate is etched anisotropically in an ICP etch (deep reactive ion etching, DRIE). The buried oxide layer of the SOI wafer serves as an etch stop layer. The 1.5µm thick buried oxide is then etched with RIE and buffered HF. The RIE was performed to remove the largest part 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 etch using the aluminium and oxide structure as a mask. This results in 20µm 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. The supporting wafer is removed after dissolving the resist in acetone.

(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 PCBs and wire-bonded. The wafer used for holding the sensors is a 300µm thick (100) silicon wafer. The holes in these wafers are etched in a KOH bath using a 2µm thick oxide layer as a mask. The fact that the holes are slanted facilitates the assembly of the sensor in the holding wafer.

2. *Hybrid assembly & installation*

A positioning table was built for assembly of the sensor. The table had 3 translational and 3 rotational degrees of freedom. The glue used for fixation was a UV-hardening epoxy, EpoTek OG-154.

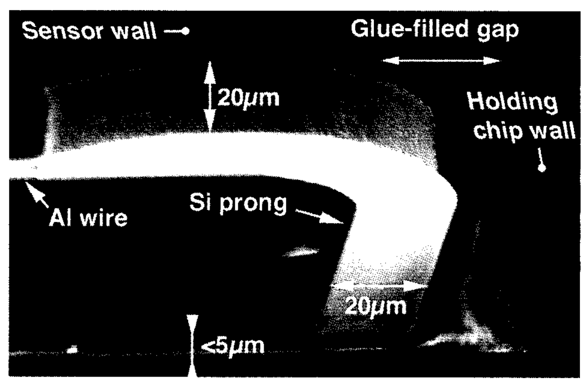

Figure 3: SEM micrograph showing a close-up of a prong

Figure 3 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. An advantage of this glue was that it could be hardened instantly, permitting a larger throughput of assembled devices. 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 on the wall of the wind tunnel.

PERFORMANCE

To verify the performance of the sensor, the velocity spectrum was measured for a turbulent flow and compared to the spectrum measured by a conventional hot-wire. Since the conventional hot-wire could not measure as close to the surface as the micromachined sensor, the measured velocities were normalized by the mean velocity at the point of measurement. Figure 4 shows the two spectrums. The RMS of the velocity measured by the conventional hot-wire is 20% of the mean velocity, while this value for the MEMS hot-wire is 39.5%. This last value complies with the correct value of 40% as calculated and measured in an investigation by Alfredsson et al. [8].

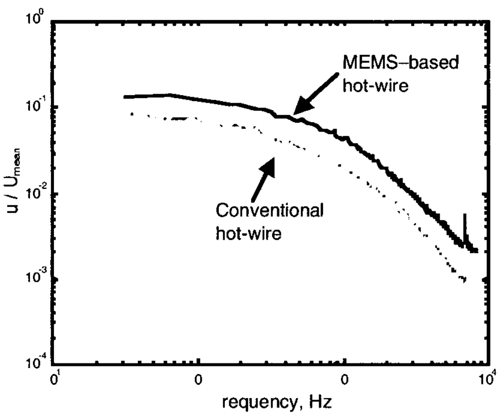

Figure 4: Velocity spectrum comparison

CONCLUSION

A micromachined hot-wire anemometer has been designed and fabricated. The wire is made of aluminium, enabling it to be used with existing CTA equipment. The largest discontinuity introduced in the system, excluding the prongs, was below 10μm,, therefore, allowing measurements to be made without interfering with the flow. We were able to manufacture devices with wire dimensions down to 1μm x 2μm x 200μm, which is the size needed to obtain the required temporal and spatial resolution for the described turbulences. The hybrid assembly method developed permits easy through-wafer contacting without compromising the flatness of the surface exposed to the airflow. Experiments in the windtunnel have verified the feasibility of the hot-wire anemometer for near-wall turbulence measurements.

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