A Silicon Wafer-Bonding Technology for Microfabricated Shear-Stress Sensors with Backside Contacts

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ABSTRACT

Measurement of shear stress is of great importance for polymer extrusion process control, and for turbulent boundary layer modeling and control for wind tunnel research. This paper describes wall-mounted sensors for both the direct and indirect measurement of shear stress. Floating-element sensors (L = 140 - 500 μm, W= 120 - 500 μm, and T= 5 μm) and hot-wire anemometers (L = 65 - 650 μm, W= 5 μm, T = 5 μm) were successfully microfabricated using silicon wafer bonding and etch-back technology. A new fabrication scheme has been developed to allow contact of the devices from the back side of the chip by implementing through-wafer vias. This was done to facilitate the packaging of these wall-mounted devices.

INTRODUCTION

Flow of fluid over a rigid surface will produce a shear stress (τ_w) on the surface, acting in the direction of the flow. This is schematically illustrated for a simple one-dimensional case in Figure 1, where the shear stress is given by

$$\tau_w \equiv (\text{ fluid viscosity }) \times (\text{ shear rate }) = \mu \cdot \left(\frac{\partial V_{||}}{\partial n}\right)$$

where $V_{||}$ is the streamwise fluid velocity and n is the direction normal to the surface. Shear stress is an important flow parameter to measure because it contains information about fluid composition (viscosity) as well as flow characteristics (shear rate).

Within many industrial extrusion processes and wind tunnel research applications, there is a growing need for wall-mounted shear-stress sensors (as in Figure 1) that allow flow properties to be measured, modeled, and controlled. A basic extrusion process involves the conversion of a suitable raw material into a product of specific cross section by forcing the material through an orifice or die under controlled conditions [1]. Shear-stress sensors can be used in extruders to determine viscosity (the near-wall fluid velocity profile is well-understood for a given extruder design), which can give an indication of the chemical composition of the polymer. For wind tunnel research, a turbulent boundary layer may extend significantly into the flow stream, but the near-wall region is considered the most important area for the production and maintenance of turbulence because this is where the maximal turbulent fluctuations and Reynolds stresses occur, and where the mean shear is the strongest [2]. Wall-mounted shear-stress sensors would provide valuable instrumentation for modeling and controlling turbulent boundary layer characteristics since they allow instantaneous shear rates to be determined (since the viscosity of air is a well-tabulated parameter). This paper describes silicon microfabricated floating-element sensors [3] (for direct shear-stress measurements) and hot-wire anemometers (for indirect shear-stress measurements) that meet the performance and packaging requirements of commercial polymer extruders (high shear-stress ~ 100 kPA, high pressure ~ 6000 psi, and high temperature ~ 300 °C) and low-speed wind tunnels (flow velocity < 40 m/s and shear-stress sensitivity ~ 1 Pa).

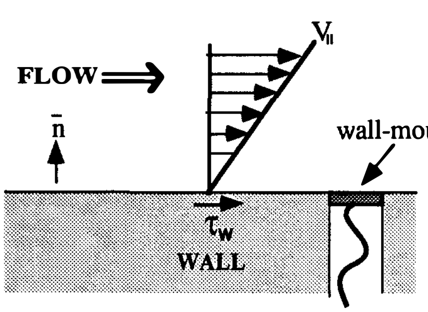

Figure 1: Schematic of a wall-mounted shear-stress sensor for determining fluid composition and flow characteristics.

It is imperative for these microfabricated shear-stress sensors that the transducer structure, the electrical connections to the sensor chip, and the sensor package do not form protrusions (even on the micron scale) that will perturb the flow characteristics of the system in the vicinity of the wall-mounted sensor. Micromachining permits the fabrication of very planar sensor structures that are compatible with this requirement, however, electrical connection often poses a problem. Previously, designers of wall-mounted flow sensors have addressed this concern by utilizing enlarged chip sizes or long probe stalks which attempt to locate the bonding pads sufficiently 'down stream' [3 - 6], or by implementing vertical integration schemes that require unique transducer materials [7]. Comparatively, a backside electrical contact scheme would also allow the transducer elements to be in intimate contact with the sensing environment while simultaneously maintaining electrical / physical isolation between the electrical leads and the sensing environment, but it does not specifically require an increase in the overall size of the flow sensor. Several types of integrated devices with backside electrical contacts have been fabricated and they have employed junction-isolated leads [8 - 10], dielectrically-isolated leads [11, 12], and thermomigrated aluminum interconnect [13]. To facilitate the packaging of our wall-mounted shear-stress sensors, we have successfully developed a new microfabrication process to allow contact of the device from the backside of the chip by anisotropic etching of through-wafer vias that utilize dielectrically-isolated leads to avoid high-temperature leakage effects associated with junction-isolated interconnect. It is a significant improvement in terms of process simplicity and yield over a previously described method [14].

SENSOR DESIGN

Floating-Element Shear-Stress Sensor

The floating-element shear-stress sensor with backside contacts was microfabricated in <100> single-crystal silicon and the structure is schematically shown in Figure 2. The sensor consists of a tethered plate, or 'floating element', which can displace laterally (as a rigid body) under a shear load against the restoring force of four tethers [3]. The pressure drop across the element induces some fluid flow underneath the plate, but the shear stress generated on the bottom of the floating element can be neglected due to the small gap size (the floating element is suspended only 1 μm above the silicon substrate). The shear force on the plate is equally distributed between the four tethers and the axial stress imparted on each tether is given by

$$\sigma_{tether} = \frac{\tau A_{plate}}{4 A_{tether}}$$

where A_{plate} is the area of the floating-element plate and A_{tether}

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DOI 10.31438/trf.hh1994.26

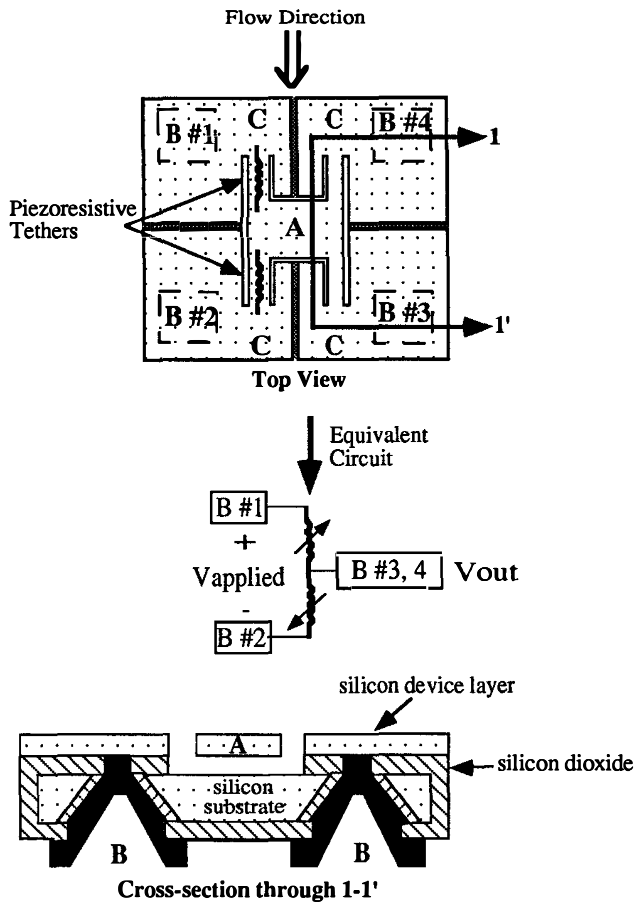

Figure 2: Top and cross-sectional schematic of the floating-element shear-stress sensor with a piezoresistive readout scheme. (Notation: A = floating-element transducer, B = backside contacts, C= microstructure anchors).

is the cross-sectional area of the tether. The resulting strain is transduced through the two piezoresistive tethers (one undergoes compressive axial strain and the other undergoes tensile axial strain). The change in the resistance of the tethers can be expressed as

$$\frac{\Delta R}{R} = G\varepsilon_{tether} = G\,\frac{\sigma_{tether}}{E_{Si}}$$

where ε_{tether} is the axial strain in a tether; G and E_{Si} are the gauge factor and Young's modulus for <110> single-crystal silicon, respectively. For a half-bridge readout configuration (as shown in Figure 2), the output response (ΔVout) is linear and is given by

$$\Delta V_{out} = \frac{V_{applied}\, G\, A_{plate}}{8\, A_{tether}\, E_{Si}} \cdot \tau .$$

To achieve the range of device sensitivities and dynamic ranges needed for polymer extrusion, two plate sizes were fabricated (120 µm x 140 µm and 500 µm x 500 µm). By simply increasing the plate size, it is possible to make a sensor which approaches the sensitivity needed for wind tunnel turbulence measurements.

Hot-Wire Anemometers

Figure 3 is a schematic of a hot-wire anemometer pair whose suspended microbridge structure is similar to surface-micromachined anemometer devices [15, 16], but in addition utilizes backside electrical contacts for flush-mounting the sensor

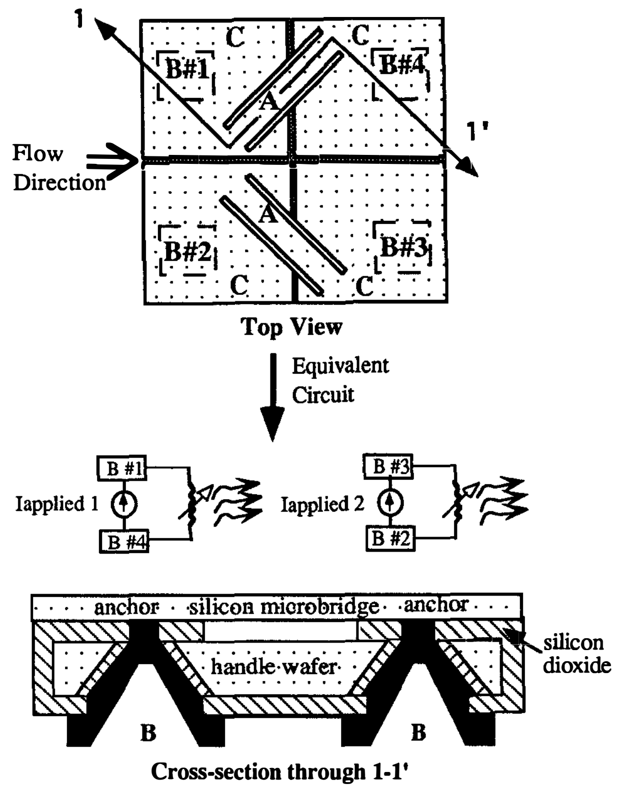

Figure 3: Schematic of the hot-wire anemometer chip. (Notation: A= hot-film element, B= backside contacts, C= microstructure anchors).

chip in a wind tunnel. The two resistive hot-wire elements are oriented at 90-degrees with respect to each other. By measuring both the common-mode and differential convective cooling of the anemometer pair, we can infer both the magnitude and direction of the local wall shear stress (assuming no reverse flow). The resistive microbridges, which form the hot-wire elements, have a nominal width of 5 µm, a nominal thickness of 5 µm, and lengths which vary (65 µm, 130 µm, 325 µm, and 650 µm) to set both the sensitivity and dynamic operating range of the devices. The resistive microbridges are electrically isolated from the handle wafer substrate and they are suspended 1 µm above the handle wafer (providing thermal isolation from the substrate). Also, the backside contacts provide a relatively large surface area for conductive heat transfer to occur between the silicon microbridge anchors and the silicon substrate. This minimizes the parasitic Joule heating of the silicon microbridge anchors (please refer to Figure 3), which can influence the overall spatial and temporal resolution of the anemometer chip. The lateral gaps around the microbridge structure are nominally 5 µm wide, which is much less than the smallest turbulent length scale of most wind tunnels (approximately 35 µm at 20 m/s). Thus, any flow perturbations due to the sensor can be safely ignored.

FABRICATION

To begin the process, a <100> silicon handle wafer is thermally oxidized (1 µm) and an oxide gap, where the suspended microstructure will reside, is formed on the front side of the wafer. Subsequently, a handle wafer contact, for electrochemical wafer thinning (ECE), is formed on the back side of the wafer. The wafer is coated with LPCVD silicon nitride and the back side is patterned and etched to expose the regions that will form the via openings, as shown in Figure 4A. Anisotropic silicon etching ($KOH{:}H_2O$) is used to form the through-wafer via holes. Figure 4B shows the handle wafer after the exposed oxide at the top of the vias is removed by wet etching. The exposed <111> via sidewalls are then oxidized (~7000 Å) to provide electrical isolation, completing the handle wafer processing (the resulting structure is shown in Figure 4C). Figure 4D shows how the front side of the handle wafer is bonded [17] to the front side of a p-type device wafer which contains a n-type diffused layer (5 µm thick). A 2.5-µm thick polysilicon layer is deposited and doped to form the interconnect for the backside contacts. The device wafer is selectively thinned back to the p-n junction using ECE techniques [18] (the backside contacts are exploited for making electrical connection to both the n-type device layer and handle wafer) and the resulting structure is shown in Figure 4E. A high-dose phosphorus implant was performed on the device layer to create the n+ diffusion interconnect while the piezoresistive tether regions are masked so they remain lightly-doped. The suspended sensor structure has been released using dry etching and it was thermally oxidized (450 Å) to form a three-dimensional passivation coating. The finished sensor is shown in Figure 4F, where individual backside contact pads have been formed, and metal (1 µm of aluminum) has been deposited and patterned to facilitate external lead attachment.

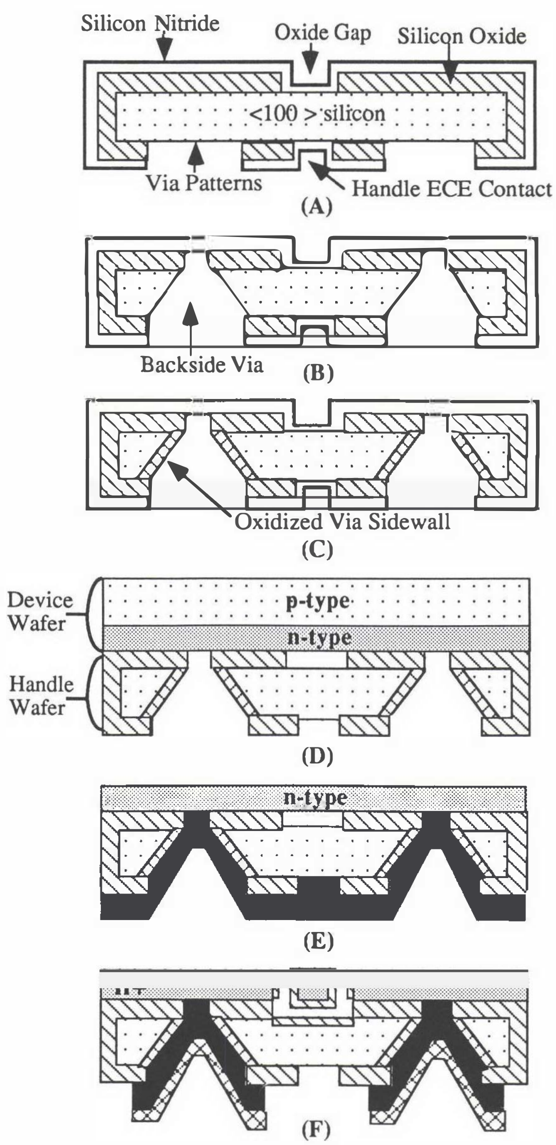

Figure 4: Sensor fabrication sequence.

The process yielded floating-element shear stress sensors and hot-film anemometers, with backside contacts that were planar microstructures. The shear stress sensor chip is 5 mm by 5 mm and a photomicrograph of a microfabricated device is shown in Figure 5 for a 120 µm by 140 µm floating element. The anemometer chip is the same size as the shear-stress sensor and consists of two hot-wire elements, as shown in the photomicrograph of Figure 6 for the 325-µm long microresistors.

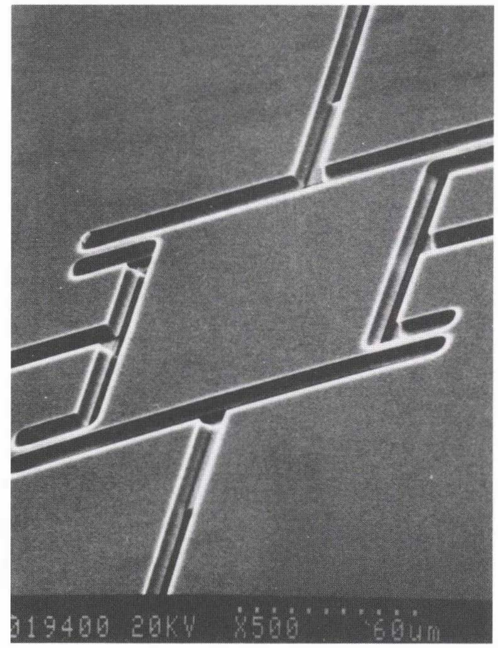

Figure 5: Photomicrograph of a microfabricated floating-element shear-stress sensor.

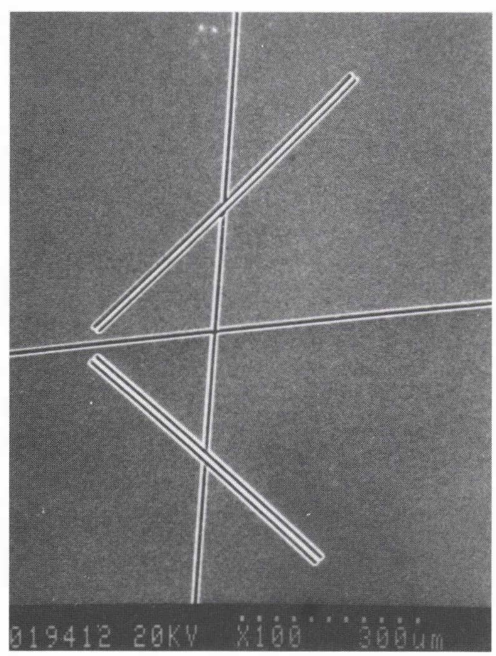

Figure 6: Photomicrograph of a microfabricated hot-wire anemometer chip.

RESULTS AND DISCUSSION

Electrical Functionality of the Devices

The sensors were probed to evaluate the electrical functionality of the backside contacts. The via resistance is composed of the ohmic losses within the through-wafer polysilicon interconnect and the lateral sheet resistance of the silicon anchors for the suspended microstructures. The via resistance was measured to be ≤ 40 Ω and it will not adversely affect performance of any of the sensors; the via resistance was calculated to be ~ 47 Ω with 99.2 % of this value attributed to the lateral sheet resistance of the silicon anchors. The via capacitance (i.e. via contact to handle wafer) was calculated to be 30 pF.

The measured microbridge resistances for the anemometers and the tether resistances for the shear-stress sensor are listed in Table 1. All measured values are within the range of expected values (within the accuracy imposed by the via resistances and process tolerances). Figure 7 shows typical measured current-voltage characteristics of a microfabricated anemometer during no-flow conditions. The curvature of the measured voltage curve (at the higher bias currents) demonstrates Joule heating of the microresistor. The incremental resistance, derived from the measured current-voltage characteristics, is also shown in Figure 7. Two features of this incremental resistance can be highlighted. First, the resistance increases due to the reduction in carrier mobility as the silicon heats. Second, at high enough temperature (~ 900 - 1000 °C), the silicon becomes intrinsic and the resistance decreases due to the extra thermally generated carriers. The linear TCR of the film was found to be $(2.2 \pm 0.4) \times 10^{-3}$ / °C which is comparable to previously published data for the TCR of homogeneously-doped silicon samples ($(1.24 - 2.13) \times 10^{-3}$ / °C, extracted from resistivity data presented in reference [19]).

Hot-Wire Element Lengths	Average Measured Element Resistance	Average Measured Tether #1 Resistance	Average Measured Tether #2 Resistance	Average Measured Half-Bridge Resistance
65 μm	398 Ω	1289 Ω	1282 Ω	2291 Ω
130 μm	732 Ω			
325 μm	1690 Ω			
650 μm	3270 Ω			

Table 1: Average measured hot-wire element resistances for various microbridge lengths (about 30 elements per microbridge length were measured) and average measured resistances of the piezoresistive tethers of the shear-stress sensors (about 22 sensors were measured).

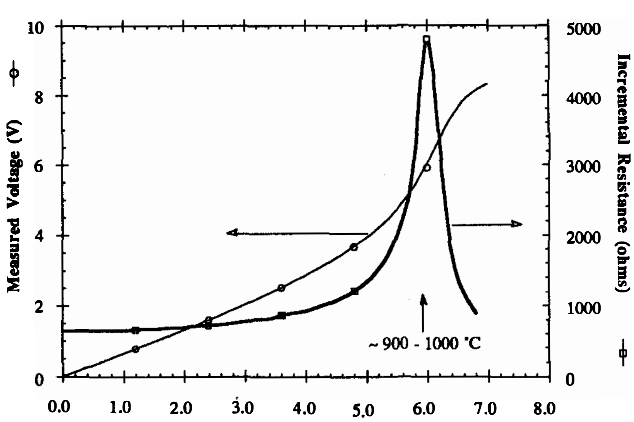

Figure 7: I-V characteristics of a 325-μm long hot-wire anemometer during no-flow conditions at room temperature.

The first fabrication run had a functional device yield which was directly related to the sensor lead count: there was a 36 % yield for the anemometer chips (composed of 2 adjacent hot-wire elements that require 2 functional backside contacts), a 50 % yield for the floating-element shear-stress sensors (require 3 functional backside contacts for operation), and a 72 % yield for the individual hot-wire elements (require only 2 backside contacts for operation). The dominant failure mode is electrical lead conduction to the substrate. We are investigating this phenomena, and are exploring process options to improve the yield.

Sensor Responses

Floating-Element Shear-Stress Sensor

Sensors with exactly the same floating-element structures, but with frontside electrical contacts, have been previously calibrated in a cone-and-plate viscometer and have shown excellent agreement with the theoretical models [3]. Those sensors had also survived an extrusion environment (up to 20 hrs. of processing time in a polyethylene resin which was temperature-cycled to 220 °C and which achieved hydrostatic pressures of 6000 psi) [3].

Currently, the new electrically-functional sensors with backside contacts are being calibrated in viscometers and are being mounted in industrial polymer extruders to evaluate their use as process control monitors. Initial shear-stress responses have been obtained by mounting the sensors in an uncalibrated nitrogen flow stream (set up on a probe station) and a typical response is shown in Figure 8. The effective shear stress was calculated, from the sensor response, to be on the order of 350 Pa and the flow noise from manual closing of the flow valve was also transduced by the sensor.

Hot-Wire Shear-Stress Sensors

A plastic plug package was designed to allow the sensors to be flush-mounted into our low-turbulence wind tunnel There was a pre-drilled channel to allow access to the backside wire leads of the sensor. Wires were silver epoxied to the backside electrical contacts of the anemometer chips. The chips were flush-mounted into the chip recess of the plug and molding clay was used to fill in the gaps and to ensure that the chip surface was flush with the surface of the plug. The plugs fit into the precisely machined openings of a plastic port flush-mounted into the wall of a flat plate (the plate forms a section of the wind tunnel wall), positioned where a clean laminar boundary layer flow is established (sensors were located approximately 1 meter from the sharp leading edge of the plate). Flow speeds varied from 1 - 20 m/s.

For initial static calibration in a laminar boundary layer, the sensors were connected to standard constant-current drive

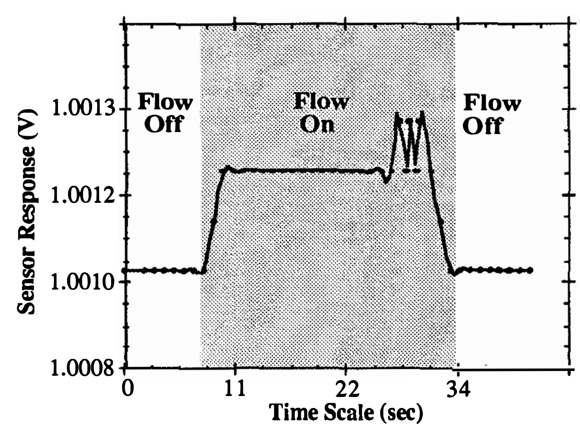

Figure 8: Response of floating-element shear-stress sensor towards uncalibrated nitrogen flow (500 μm X 500 μm plate size, with $V_{applied}$ = 2V).

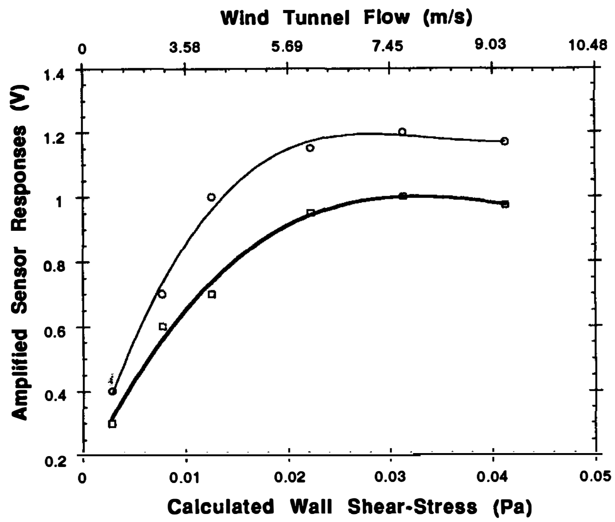

Figure 9: Characteristic laminar flow response of an anemometer chip (composed of two 325-μm long hot-wire elements). The calculated wall shear stress is referenced against the wind tunnel flow rate (scale is non-linear).

circuitry [20] and the chips were manually oriented toward the flow as shown in Figure 3. The anemometers are functional as velocity sensors and their responses (as in Figure 9) are characteristic of constant-current mode hot-wire anemometers [20]. We believe that the variation in the individual hot-wire responses can be attributed to a slight mis-alignment of the chip toward the flow stream. Because the laminar boundary layer was previously confirmed to be a Blasius boundary layer, wall shear stress can be inferred from the near-wall velocity profile (please refer to [21]), and the shear-stress responses of the sensors can also be determined (as shown in Figure 9). Since it was demonstrated that the anemometers with backside contacts are functional sensors, constant-temperature drive circuitry is currently being designed to more effectively evaluate the dynamic response characteristics of the sensors and to allow measurements to be taken in turbulent boundary layers.

CONCLUSION

We demonstrate the feasibility of microfabricated floating-element and hot-wire anemometer shear-stress sensors with a novel backside contact scheme. The electrical functionality and initial response characteristics of both types of flush-mounted sensors were established. Currently, the calibrated response characteristics toward shear-stress fluctuations within a polymer extruder and a wind tunnel turbulent boundary layer are being experimentally determined for the floating-element and hot-wire anemometer sensors, respectively. This new backside contact method readily lends itself to forming other microsensors (i.e. temperature and pressure), with backside contacts, that would expand the quantitative process-control arena for extrusion processes and would provide multi-sensor arrays for wind tunnel turbulence research.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of this work by the 3M Corporation, A.F.O.S.R., and the NSF Presidential Young Investigator Award Program (Prof. Schmidt). The authors would like to thank Dr. John Huizinga, Andrew Cipra, and Glen Merfeld (of 3M) for their assistance and significant involvement with the floating-element shear-stress sensor calibration and testing issues. All microfabrication was done in the Microsystems Technology Laboratories.

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