DEVELOPMENT OF A HYDRAULICALLY SMOOTH WALL SHEAR STRESS SENSOR UTILIZING THROUGH SILICON VIAS

*C.A. Barnard, D. Mills¹, J. Meloy², and M. Sheplak**

Interdisciplinary Microsystems Group, University of Florida, Gainesville, Florida, USA

ABSTRACT

This paper describes the development of a wall shear stress sensor system designed to be fully non-invasive to low-speed aerodynamic flows. The microelectromechanical systems (MEMS) sensor is fabricated with integrated through-silicon-vias (TSVs), eliminating the need for front side wire bonds. Packaged in a modular housing with interchangeable components, the result is a device with less than 50 μm of deviation over the wetted surface, satisfying the requirements of hydraulic smoothness for flow speeds less than 30 m/s. Sensor performance includes a sensitivity of 1.36 mV/Pa at 1.128 kHz, corresponding to a minimum detectable signal of 1.1 mPa, resonance of 3.4 kHz with a 1.5 kHz flatband, and 72 dB of pressure rejection.

INTRODUCTION

Despite years of effort, the ability to make continuous real-time direct measurements of wall shear stress with both mean and fluctuating components remains elusive [1],[2]. Because of this, investigations into fundamental fluid flow problems are often hindered. An instrumentation-grade tool to precisely measure wall shear stress would enable further research in the areas of skin friction drag and turbulent boundary layer analysis [3].

For accurate measurement of fluid-wall interactions in a turbulent flow field, it is essential that the installed sensor be non-invasive, or hydraulically smooth, so as to not corrupt the flow measurement [4]. Hydraulic smoothness requires a surface roughness less than 5 viscous wall units, which for typical low-speed wind tunnel applications (e.g., Reynolds number $\sim 2,500$) is ~ 50 -100 μm . Wall shear stress sensors with integrated TSVs have been previously reported only for polymer extrusion applications [5].

Given this limitation, and considering the small magnitude forces of aerodynamically generated wall shear stress, a MEMS-based differential capacitive floating element design retains the most promise. The work presented here is a continuation of prior efforts from Chandrasekharan et. al [6], and Meloy et al [7]. Previous sensors made use of frontside wire bonds for electrical connections to the silicon electrodes, which require encapsulation for flow protection and extend above the surface well over 500 μm . Additionally, improvements to the interface circuitry design reduce the electronic noise floor to increase the dynamic range.

STRUCTURE AND DESIGN

The overall sensor structure is composed of three parts: the floating element, interdigitated comb fingers, and supporting tethers. An analytical mechanical model of the dynamic and static sensor response can be found in [6]. An image of a fabricated device under a microscope is seen in Figure 1.

The floating element acts as the primary flow interface, providing a surface for wall shear stress to act upon. Pressure release holes throughout the surface assist in equilibrating normal pressure across the floating element. Their diameter, 5 μm , is small enough to remain hydraulically smooth and not significantly alter the effective wetted surface.

Figure 1: Microscope image of wall shear stress sensor.

Interdigitated comb fingers on either side of the element act as variable gap capacitors. Set in a differential orientation, when the floating element deflects in a streamwise direction the gap between one set of fingers will shrink and the opposing gap widens. The benefits of a differential setup include rejection of common mode inputs, including pressure, and doubling of the overall sensitivity. Furthermore it allows for proper retention of input phase and thus the single-axis direction of wall shear stress at the sensor location.

The supporting tethers are arranged in an H-bar structure format as seen in Figure 1. Modeled as a clamped-clamped beam, the tethers act as a restoring spring in the primary flow direction, and work to reject normal pressure and cross-axis shear inputs. Optimization of the sensor's operational space focuses primarily on tether width. A narrower tether reduces structural stiffness, increasing sensitivity, while a wider tether increases the resonance and bandwidth.

FABRICATION

The sensor is fabricated using a six-mask process, starting with a silicon-on-insulator (SOI) wafer with an n-doped 50 μm device layer on top of a 1 μm buried oxide (BOX) and 400 μm handle. Integrated poly-silicon (Si) TSVs, doped with red phosphorus to a resistivity of <0.005 ohms-cm, are isolated from the handle layer by 1 μm of thermal oxide and directly connected to the device layer to improve conductivity. Wafers were sourced from IceMOS Technologies with TSV fabrication already completed.

The remaining fabrication steps are carried out at the University of Florida Nanoscale Research Facility (NRF). A buffered oxide etch (BOE) is first used to clear out backside contact windows over the TSVs, while the frontside oxide is completely stripped. A 0.5 μm Al/Si (2%) layer is sputtered on both sides of the wafer. Bond pads are patterned and etched as 250 μm squares over the TSV contacts. A protective layer of silicon nitride, 800 nm thick, is then deposited on the backside using plasma-enhanced chemical vapor deposition (PECVD).

To ensure ohmic contact between the TSVs and bond pads, a series of current-voltage (I-V) curve measurements are made with a HP4154 Semiconductor Parameter Analyzer. Test structures include sets of resistive elements in series utilizing 2, 4, 8, 16, 32, or 64 TSVs. Total resistance measurements are normalized by the number of TSVs used. After initial measurements are performed the wafers are annealed in forming gas (95% nitrogen and 5% hydrogen) at 450C for 60 minutes and the resistance measurements are repeated. This process is repeated until the contacts are ohmic.

Sequential deep reactive-ion etch (DRIE) masks are then used for frontside floating element definition and backside cavity etching. Device separation is achieved during these cycles as well, with ‘dicing’ streets included in the exposed areas. A BOE etch releases the floating elements and separates the individual die, which are held to a carrier wafer with Nitto-Denko thermal release tape. Final clearout of the BOX near the base of tethers is completed with a reactive-ion etch (RIE). A schematic of the final device, and its first level of packaging, is shown in Figure 2.

Figure 2: Simplified schematic of six-mask fabrication performed at UF Nanoscale Research Facility.

Die selection is carried out as a two-step process. Physical quality of the sensor is assessed with electrostatic actuation. With the die placed under a microscope, a 2 Hz square wave is placed across each capacitive gap. If structurally sound movement is observed, and there are no cracks or defects in the floating element, the sensor is set aside for electrical impedance testing. A measured phase delay greater than 80 degrees is interpreted as nominally a capacitive impedance, without spiking or shorting through the TSV isolation oxides.

INTERFACE CIRCUITRY

The interface circuitry includes a voltage follower amplifier circuit collocated inside the cylindrical sensor housing, and an external synchronous modulation and demodulation circuit (SMOD/DMOD) [8]. Together, the system allows for real-time data acquisition at baseband frequencies far away from the experimental setup.

Situating a voltage follower directly behind the sensor die reduces the effect of signal degradation from transmission over long distances. The experimentally verified impedance of the sensor electrodes is $O(10 \text{ pF})$. An Analog Devices AD8022 operational amplifier is selected for its well-matched input capacitance and overall low noise floor. Theoretical predictions indicate minimal signal loss with cable lengths up to 50 m.

As a capacitive sensor with the intention of measuring both mean and dynamic inputs, a standard DC biasing scheme is unsuitable. To avoid the undefined impedance of a capacitor at DC, a sinusoidal biasing scheme is utilized. The SMOD/DMOD circuit is composed of four main blocks: oscillator and bias generation, timing control, filtering and conditioning, and active rectification.

A crystal oscillator generates a low-amplitude sinusoidal signal at 1 MHz. A series of adjustable gain amplifiers allow for production of two 180° phase-shifted 1 MHz carrier signals, typically set to 8 V amplitude, which are supplied to the sensor's fixed electrodes. Simultaneously, a phase-locked 5 V square wave is generated as a timing control signal for rectification. Both the duty cycle and relative phase offset of this signal are adjustable, and tuned for maximum signal to noise (SNR) performance during calibrations.

As the modulated signal is returned from the sensor amplifier, a bandpass filter removes residual DC components, low noise content, and carrier signal harmonics. A secondary gain stage further increases SNR before demodulation, accomplished with an active envelope detector. The gained signal is split, with one output buffered and the other inverted. A switch, controlled by the timing control signal, incorporates the two split signals. The result is a rectified carrier signal wave, with the envelope defined by the baseband signal content. Mean wall shear stress inputs, resulting in static changes in the nominal capacitive gaps, change the amplitude of the passed carrier wave. Low pass filtering of the rectified signal completes the demodulation, removing the carrier signal component entirely. The final system output is baseband wall shear stress information in real time, containing both mean and dynamic components.

PACKAGING

Packaging is achieved with a three-part modular approach, consisting of the sensor head, amplifier housing, and cabling connector, with a representative schematic seen in Figure 3. External packaging dimensions are 0.5" in diameter and 2" in length for the total aluminum cylinder tube.

The sensor module itself is a four-part assembly, consisting of a sensor die, a supporting substrate for electrical interconnect, a shim cap for flushness, and a metal housing. Figure 4 shows a schematic of the sensor cap attachment. A micro-milling machine is used to recess a rectangular pocket in a circular FR-4 disk. Epoxy film, chosen with a coefficient of thermal expansion minimizing mismatch between the silicon and FR-4 interface, is placed in the recess. A flip-chip bonder places the sensor die into the milled pocket of the FR-4 support substrate, with the heated chuck curing the epoxy film. Electrical connections are made from the backside of the sensor die to the FR-4 bond pads. Shim caps are machined from plastic stock with a picosecond laser system,

and affixed around the die. The entire disk is placed into a milled recess of the aluminum end cap, and pressed down for flushness.

Figure 3: Schematic of three part packaging, with sensor cap recessed into removable module housing.

Figure 4: Schematic of sensor cap assembly. The fabricated sensor die is affixed and electrically connected to the PCB, with a surrounding shim cap for flushness.

The buffer amp module is a hollow tube of aluminum which houses the amp board. Included with the AD8022 are power line filtering capacitors and a bias resistor to provide a path for dissipation of DC charge. Wiring connections to the sensor and cabling modules affix to either end of the amp board. Cabling is provided with LEMO style end connectors, with interchangeable total cable lengths, as seen in Figure 5.

Figure 5: Packaged and assembled sensor, ready for installation.

Scanning white light interferometry (SWLI) measurements of this packaged cap, shown in Figure 6, indicate a hydraulically smooth front surface for low-speed flows. Maximum step deviations are roughly $50 \mu\text{m}$, occurring at the junction between the metal housing and shim cap. Overall roughness is below $5 \mu\text{m}$. The majority of this roughness is found on the face of the metal

housing. Higher tolerances during machining, or a secondary polishing stage before assembly, will likely lead to a more planar surface.

Figure 6: SWLI measurement of packaged sensor module, with X-Profile map included. The sensor die surface is used as a zero-offset reference level.

SENSOR CALIBRATION

To characterize the dynamic wall shear stress response of the system, the shear stress field within an acoustic plane wave tube is utilized [9]. This method takes advantage of Stokes' layer excitation to generate a known oscillating wall shear stress based on measurements of maximum end wall pressure.

The wall shear stress sensor is located at a quarter wavelength away from the sound hard termination for the frequency of interest. This situates the sensor at a pressure minima node, corresponding to a maxima in velocity and shear. The result is acoustic excitation of the sensor with tangential shear with reduced normal pressure loading, mitigating cross-axis inputs during testing.

Figure 7: Sensitivity calibration results at 1.128 kHz. Linear fit to points above the noise floor in red correspond to a sensitivity of 1.36 mV/Pa .

By increasing the sound pressure level driven by the speaker, the dynamic sensitivity of the sensor is determined. A calibration frequency of 1.128 kHz is used. At a carrier signal bias level of 8 V amplitude, the sensitivity is measured as 1.36 mV/Pa, shown in Figure 7. The response is linear up to the bounds of the testing platform of 2.18 Pa for 66 dB of experimentally verified dynamic range. Theoretical predictions indicate the onset of non-linear response at 100 Pa, corresponding to a dynamic range of 100 dB.

A noise floor measurement is displayed in Figure 8. Data is sampled with a SRS780 (Stanford Research Systems) dynamic signal analyzer utilizing 800 FFT lines over various frequency spans. To eliminate EMI effects, the wall shear stress sensor and interface circuitry are placed within a double Faraday cage. With a measured noise floor of 1.5 μV at 1.128 kHz, the corresponding minimum detectable signal is 1.1 mPa.

Figure 8: Noise floor of fully assembled wall shear stress sensor system. At the calibration frequency of 1.128 kHz, the noise floor is 1.5 μV , for a MDS of 1.1 mPa.

A similar methodology is used to characterize the frequency response function of the device. The static end wall termination is replaced with a variable termination that moves axially along the duct. By keeping the wall shear stress sensor at a fixed location along the tube length, and adjusting the axial distance of the end wall, the shear sensor is kept at a pressure node for all frequencies. A frequency response function is constructed using the single-frequency sensitivity as a reference. The resonant peak of the sensor is identified at 3.4 kHz, with a useable flatband extending to 1.5 kHz.

Sensitivity to normal pressure is characterized by mounting the shear sensor in the end wall of the plane wave tube. In this orientation the floating element is subjected to normally incident sound waves with no tangential shear, and repeating the procedure yields system sensitivity to pressure. A pressure rejection ratio of 72 dB is observed.

CONCLUSIONS

The sensor described herein is the first hydraulically smooth wall shear stress sensor for use in low-speed wind tunnel applications. SWLI measurements verify a maximum step height of less than 50 μm across the 0.5" diameter package. Specialized interface circuitry leverages an amplitude modulation approach to deliver continuous real-time measurements of wall shear stress with directional mean and dynamic information included. Overall performance specifications are consistent with other MEMS

sensors described in the literature, including a sensitivity of 1.36 mV/Pa, MDS of 1.1 mPa, and bandwidth of 1.5 kHz.

Future work will focus on experimental verification of performance inside full scale wind tunnels, and a transition to commercially available instrumentation. Extension of measurement capabilities to both tangential in-plane directions would provide a true vector measurement of wall shear stress.

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CONTACT

*M. Sheplak, tel: +1-352-392-3983; sheplak@ufl.edu

¹ Currently with Interdisciplinary Consulting Corporation (IC2), Gainesville, FL, USA

² Currently with Boeing Corporation, Seattle, WA, USA