DESIGN, FABRICATION, AND CHARACTERIZATION OF PIEZORESISTIVE MEMS SHEAR STRESS SENSORS

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ABSTRACT

This paper presents the design, fabrication, and characterization of unique piezoresistive microfabricated shear stress sensors for direct measurements of shear stress underwater. The uniqueness of this design is in its transduction scheme which uses sidewall-implanted piezoresistors to measure lateral force (and shear stress), along with traditional top-implanted piezoresistors to detect normal forces. Aside from the oblique-implant technique, the fabrication process also includes hydrogen anneal step to smooth scalloped silicon sidewalls due to Deep Reactive Ion Etch process, which was shown to reduce 1/f noise level by almost an order of magnitude for the sidewall-implanted piezoresistors. Lateral sensitivity characterization of the sensors was done using a microfabricated silicon cantilever force sensor, while out-of-plane characterization was done using Laser Doppler Vibrometry technique. In-plane sensitivity and out-of-plane crosstalk were characterized, as well as hysteresis and repeatability of the measurements. The sensors are designed to be used underwater for various applications. Keywords: shear stress sensor, piezoresistive, oblique implant, in-plane force, MEMS.

INTRODUCTION

Micro Electromechanical Systems (MEMS) shear stress sensors offer the potential to make measurements in fluid with unprecedented sensitivity, spatial, and temporal resolution. Most MEMS shear stress sensors have been developed for measurements in air [1-7] and utilize indirect methods. Naughton et. al. highlighted the need for further work on MEMS scale direct measurement methods [8]. Substantial work on thermal based sensors (hot wire/film anemometry) has been presented, but these devices require a priori knowledge of flow profiles, in situ calibration under identical conditions, and are limited by heat transfer in water [9].

![Fig. 1: Piezoresistive floating-element shear stress sensor](image-url)
mass transfer. While momentum transfer in wave-driven flow has received much attention, the effect of wavy flow on mass transfer is an open question in the fluid mechanics community. Our goal is to demonstrate arrays of these sensors to allow the first direct measurement of shear stress profiles under unsteady wave-driven flow over a coral reef canopy (natural rough surfaces), as well as in oscillatory flowing cell-culture, and cardiovascular mockups. Robust underwater shear stress sensors are required for measurements with fine spatial, ~100 µm to 1 mm, and temporal (1-10 kHz) resolution, as well as sensitivity over the range of 0.01-100 Pa. These sensor arrays provide an exciting platform to explore factors affecting wall shear stress, such as roughness, floating element and gap size, as well as spatial variation along and across the flow. The sensors will allow detection of flow reversals in turbulent flow and normal force due to flow separation.

NOMENCLATURE

\( F_z \) Resultant fluid shear force acting on the top surface of \( \frac{3}{4} \) of the plate element
\( F_y \) Resultant fluid normal force acting on the top surface of \( \frac{3}{4} \) of the plate element
\( p \) Resultant fluid shear force acting on the top surface of a single tether
\( M_y, M_z \) Bending moment at the root of the tether
\( \sigma_{xx} \) Bending stress at the root of the tether
\( I_{yy}, I_{zz} \) Area moment of inertia of the tether’s cross section
\( \gamma, \delta \) \( \frac{1}{2} \) of the tether’s thickness or width
\( L \) Length of the tether
\( w \) Width of the tether
\( t \) Thickness of the tether
\( \rho \) Resistance of the piezoresistor
\( \pi_l \) Longitudinal piezoresistance coefficient
\( E \) Young’s Modulus of Silicon (~161 GPa)
\( h \) Thickness of a cantilever beam
\( b \) Width of a cantilever beam
\( l \) Length of a cantilever beam

DESIGN

The floating element sensor concept [1, 5–7] consists of a plate element suspended by four tethers (Fig. 1). Capacitive and optical methods as transduction schemes have been integrated with this geometry in the past to measure shear stress directly [1, 6, 7]. The uniqueness of this design is its transduction scheme which uses sidewall-implanted piezoresistors [10] to measure lateral force (and shear stress), along with traditional top-implanted piezoresistors to detect normal forces. Piezoresistors are placed at the root of each tether from which shear stress can be inferred. Each sensor measures normal and lateral forces simultaneously. The orientations of the piezoresistors were chosen such that two of them are sensitive to lateral (along the flow direction), while the other two are sensitive to out-of-plane deflections. Each tether was modeled as a fixed-guided beam (fixed at one end to the substrate and guided at the other end by a quarter of the plate element). As fluid flows on top of the sensor, it exerts shear stress on the top surface (plate element and tethers), causing the tethers to bend. Equations 1a and 1b show bending moments due to the resultant fluid forces. The stress at the root of the tether where the piezoresistor is located can be calculated (Eq. 2), then the change in the resistance of the piezoresistor due to applied stress is determined (Eq. 3). The piezoresistors are oriented along the <110> direction of (100) p-Silicon, which gives the maximum value for \( \pi_l (~71 \times 10^{-12} \text{ cm/dyne}) [11] \).

\[
M_{\text{guided-end}} = \frac{FL}{2} + \frac{pL^2}{6} \quad [\text{Eq. 1a}]
\]

\[
M_{\text{fixed-end}} = \frac{FL}{2} + \frac{pL^2}{3} \quad [\text{Eq. 1b}]
\]

\[
\sigma_{xx} = \frac{M_y\gamma}{I_{yy}} \quad [\text{Eq. 2a}]
\]

\[
\sigma_{xx} = \frac{M_z\delta}{I_{zz}} \quad [\text{Eq. 2b}]
\]

\[
\Delta \rho = \pi_l \sigma_{xx} \quad [\text{Eq. 3}]
\]

Arrays of various sensor designs were designed and fabricated to evaluate parametric effects at the microscale, including: dimensions of the tethers (264-1236 µm long, 7-15 µm wide, and 7-12 µm thick), plates (40-1030 µm square), and their ratios (0.1-5); gap sizes (5-20 µm); and geometry (squares, rectangles). Experimental studies of error sources for skin-friction moment balance measurements by Allen [12] and Haritonidis [13] found that larger gap size is preferable to the smaller one. However, both of these empirical results are based on supersonic airflow (e.g. Mach number 2.37 [12]). The applicability of this empirical data to the underwater sensors is not known, thus gap size effect will be studied.

FABRICATION

The fabrication process (Fig. 2) starts with 4” n-type (Ph-doped) double-polished (100) Silicon-on-Insulator (SOI) wafers. The resistivity of the device layer of the SOI wafers was ~18 ohm-cm. The device layer thickness, which determines the thickness of the tethers and the plate element, was 7, 10, and 12 µm (with 10 µm to be the optimum design). The handle layer and the buried oxide thicknesses were 300 and 0.5 µm, respectively.

Alignment marks were patterned on the wafers. Next, roughly 250 Å of thermal oxide was grown at 850°C for 13 minutes as a protective/screening oxide for the subsequent ion implant steps. The screening oxide was intended to minimize damage of the silicon lattice. Ion implantation forms the top piezoresistors and the conducting regions. Both implants (Boron) were done at 50 keV and 7°-angle from the normal axis to minimize channeling. The doses used were 1x10^15 and 1x10^16 cm^-2 for the top piezoresistor and the conducting regions, respectively. Both implants were annealed using Rapid Thermal Anneal (RTA) process at 1050°C for 75 seconds. Then, the screening and the RTA-oxide were etched away. About 1.1 µm of Low Temperature Oxide (LTO) was deposited at 400°C for the preparation of side-wall implant. LTO and silicon were then etched to pattern the geometry of the sensor using oxide plasma etch and Deep Reactive Ion Etch (DRIE), respectively. The etched trenches become the gap between the sensors and the silicon substrate. In order to smooth the side
wall from the resulting scallops due to DRIE process, the wafers were Hydrogen-annealed at 1000°C and 10 mTorr for 5 minutes [14]. Figure 3 shows the side wall roughness before and after the hydrogen anneal. The top surface was then covered with photoresist and an opening near the root of each tether was patterned to allow for an angled ion implant at 20 degrees from the normal axis. Boron, with dose of $4 \times 10^{15}$ cm$^{-2}$, was implanted at 40 keV. After stripping the photoresist and LTO, the side-wall implant was annealed using RTA process at 1050°C for 75 seconds. Passivation oxide was thermally grown to about 2100Å at 1000°C for 30 minutes, including post-oxidation inert anneal for 5 minutes. Next, the passivation oxide was patterned and etched to open electrical connection from aluminum to the conducting region. About 1 µm of 99%-Aluminum/1%-Silicon was sputtered, patterned, and etched back. The sensors were then released from the backside using DRIE process. Finally, the wafers were forming gas (hydrogen) annealed at 400 °C for 2 hours. Fig. 4 shows Scanning Electron Microscopy (SEM) images of the released sensors.

CHARACTERIZATION

The sensor (500-µm floating element size, 10-µm tether width and thickness) was calibrated using a microfabricated piezoresistive 15µm-thick silicon cantilever force sensor (Fig. 5). The equivalent spring constant of the force sensor, $k$, was calculated from beam theory (Eq. 4) and cantilever force sensitivity [~41.57 kV/N – with 200X bridge output amplification] was subsequently calibrated using a Laser Doppler Vibrometer (Polytec OFV3001) and resonance technique, for details of the sensors and method see [15, 16].

$$k = \frac{Ebh^3}{4l^3}$$  \[Eq. 4\]
perpendicular to the cantilever (Fig. 6). The tip of the cantilever was carefully inserted from the top into the gap of one of the sensors with larger gap size, 20 µm (Fig. 7). The image in Fig. 7 was taken using a Leica DM IRB 20X inverted microscope and the image shown is the bottom view of the sensor and the cantilever. The width and the thickness of the cantilever are 400 and 15 µm, respectively. The size of the shear sensor floating plate element used in this experiment was 500 µm x 500 µm.

The cantilever was then moved to the left (as seen in Fig. 7) by a piezoactuator (PIHera P622.Z) with control electronics (E-505) in increments of 1 µm from 0 to 200 µm, pushing against the sensor (the plate element). The shear sensor is ~200 times stiffer than the cantilever and the applied displacement may be approximated as accommodated completely by deflection of the cantilever. Thus, moving the cantilever a known distance applies a well characterized force to the shear sensor in the in-plane direction (with some error due to torsion of the cantilever as one corner always contacts first). Resistance change proportional to stress in the piezoresistors is conditioned with a Wheatstone bridge and the voltage outputs from the shear stress sensor piezoresistors and the cantilever force sensor are recorded using LabView during the experiments. Force is inferred from the cantilever voltage and sensitivity of the shear stress is then inferred from data as in Fig. 8. The elapsed time for each 1µm piezoactuator step was 0.5 seconds; however, data were taken over the last 0.1 seconds to reduce the effects of ringing, and data taken at 2400 Hertz for 0.1 seconds were averaged to give a single data point for each piezoactuator step. The large noise component is likely due to low mechanical stiffness (ringing) in the experimental setup, slippage of the cantilever to plate contact during the test and uncontrolled light and electromagnetic noise sources. This particular sensor has an in-plane sensitivity of about 50 mV/µN. The crosstalk of the top-implant piezoresistor to in-plane force is also quite low, about 0.8 mV/µN, confirming low sensitivity to off-axis loads. The in-plane force sensitivity of the side wall implant translates to 0.063 mV/Pa (before any amplification). The theoretical value was found from Eq. 3 and 4 and predicted to be 0.1 mV/Pa.

Figure 9 shows the typical hysteresis and non-linearity curve of the measurements. Figure 10 shows the trendlines repeatability of five sequential measurements of shear sensor output over the piezoactuator displacement range. The trendlines were generated based on the data from 50 to 150 µm of piezoactuator displacement. This was done to minimize the effect of imperfect contact between the cantilever and the plate element in the first 50 µm and to satisfy small angle deflection assumption of the cantilever.

Figure 7: The white regions are the gaps and the rectangular feature in the right gap is the cantilever. Only half of the sensor plate element and two tethers are visible.

Figure 8: In-plane and out-of-plane sensitivities to in-plane motion (based on the slopes) are 50.3 and 0.8 mV/µN.

Figure 9: Typical hysteresis and non-linearity curves of the measurements.
The sensitivity of the top-implanted piezoresistor to normal force was characterized using a benchtop calibration technique [16]. The sensor was mounted on a microscope slide and driven in out-of-plane motion by a Jodon EV-30 piezoelectric shaker while a Laser Doppler Vibrometer (Polytec OFV3001) was used to extract the average velocity of the plate element. The Vibrometer was set to 5 mm/s. Both signals from the Vibrometer and the conditioned output of the Wheatstone bridge (which was amplified 1000X using AD624) were captured using HP 54542A Oscilloscope (Fig. 11). The sensor sensitivity was found to be about 0.04 mV/Pa before any amplification.

![Fig. 10](image)  
**Fig. 10:** Repeatability of the five sequential measurements. The trendlines are normalized due to DC offsets caused by an unbalanced bridge at the beginning of the runs. The typical standard error of the slope was found to be 0.0022 V/µm.

![Fig. 11](image)  
**Fig. 11:** Response curves from the Vibrometer and the top implanted piezoresistor to normal force. The sensitivity is ~40 mV/Pa. The two curves have 90° phase shift and are proportional to plate velocity and strain at the root of the tether.

Piezoresistors are sensitive to electromagnetic noise and temperature. A simple experiment was set up to characterize the sensitivity of the piezoresistor with respect to change in temperature. The sensor was submerged in a deionized water bath (in a beaker) and enclosed by a foil-wrapped box to avoid contribution of electromagnetic interference to the change in resistance. The temperature of the water bath was monitored using a thermometer with a resolution of 0.5 °C. The bath was slowly heated using a hotplate to 50°C and cooled down by adding ice to about 10°C. The change in resistance was monitored using a HP34401A Digital Multimeter (DMM). Fig. 12 shows the change in resistance with respect to change in temperature for three different runs. The temperature coefficient of sensitivity was found to be 0.0081 kΩ/°C, which translates to about 30 Pa/°C. Therefore, temperature compensating signal conditioning will be used for underwater measurements.

![Fig. 12](image)  
**Fig. 12:** Plot of the change in piezoresistance with respect to the change in temperature for three different runs. Temperature coefficient of sensitivity was found to be 0.0081 kΩ/°C.

The noise measurements were done using Stanford Research Systems SR570 current preamplifier to extract the noise spectra of the piezoresistors. A current is fed into the SR570, which converts this current to a voltage. An HP89441A vector signal analyzer was used to find the power spectral density per decade. Fig. 13 shows the diagram of the setup. During the experiment, the sensor was encapsulated by an aluminum foil-covered box to avoid noise contributions due to electromagnetic interference. Fig. 14 shows almost an order of magnitude improvement on the 1/f noise level of the sidewall-implanted piezoresistors before and after hydrogen anneal. This support reports that surface roughness effect plays a major role in the 1/f noise level in ion-implanted piezoresistors [17].

![Fig. 13](image)  
**Fig. 13:** Diagram of noise measurement setup
Fig. 14: The noise measurements were done using Stanford Research Systems SR570 current preamplifier. Roll-offs at high frequency is due to low-pass filter in the low-noise mode operation of SR570.

CONCLUSION AND FUTURE WORK

A piezoresistive MEMS shear stress sensor for underwater applications has been designed, fabricated, and characterized. Novel fabrication techniques include oblique implant of piezoresistors and hydrogen anneal to smooth scalloped silicon surface resulted from DRIE process. Sensitivity of the sidewall-implanted piezoresistors to normal and lateral force has been characterized. Further characterization and underwater testing of the devices is underway.

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