Design and characterization of microfabricated piezoresistive floating element-based shear stress sensors

A. Alvin Barlian *, Sung-Jin Park, Vikram Mukundan, Beth L. Pruitt

Department of Mechanical Engineering, Mechanics and Computation Group, 496 Lomita Mall #262 (Durand Building), Stanford University, Stanford, CA 94305, USA

Received 1 March 2006; accepted 11 April 2006
Available online 9 June 2006

Abstract

This paper presents the design, fabrication, and characterization of unique piezoresistive microfabricated shear stress sensors for direct measurements of shear stress underwater. Sidewall-implanted piezoresistors measure lateral force (integrated shear stress) and traditional top-implanted piezoresistors detect normal forces. In addition to the oblique-implant technique, the fabrication process includes a hydrogen anneal step to smooth scalloped silicon sidewalls left by the deep reactive ion etch (DRIE) process. This step was found to reduce the 1/f noise level by almost an order of magnitude for the sidewall-implanted piezoresistors. Lateral sensitivity was characterized using a microfabricated silicon cantilever force sensor. Out-of-plane sensitivity was evaluated by laser Doppler vibrometry and resonance of the plate element. In-plane sensitivity and out-of-plane crosstalk were characterized, as well as hysteresis and repeatability of the measurements. TSUPREM-4 simulations were used to investigate the discrepancies between the theoretical and experimental values of sidewall-implanted piezoresistor sensitivity. The sensors are designed to be used underwater for studies of hydrodynamic flows.

Keywords: Shear stress sensor; In-plane force; Out-of-plane force; Piezoresistors; Piezoresistive; Ion implantation; Oblique-implant; Underwater; Floating element; MEMS; Micromachined

1. Introduction

Micro electromechanical systems (MEMS) shear stress sensors offer the potential to make measurements in fluid with unprecedented sensitivity, as well as spatial and temporal resolution. Many MEMS shear stress sensors have been developed for measurements in air [1–7] and utilize indirect methods [2–4]. Recently, Naughton and Sheplak 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].

Sensors presented in this paper are designed to study the effect of hydrodynamics and surface roughness on flow profiles and mass transfer [10]. While momentum transfer in wave-driven flow has received much attention, transport in unsteady flow over rough surfaces is an open question in the fluid mechanics community. A goal of this work is to demonstrate arrays of floating element sensors to allow the first direct measurements of shear stress profiles under unsteady, wave-driven flow over a coral reef canopy (natural rough surface). Future applications may be extended to monitoring oscillatory flowing cell-cultures or verifying flow simulations in cardiovascular mockups. Robust underwater shear stress sensors are required for measurements with targets of fine spatial, ~100 μm to 1 mm, and temporal resolution, 1–10 kHz, 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. Floating element sensors also allow detection of flow reversals in turbulent flow and normal forces due to flow separation.
Nomenclature

\( A_p \) area of the top surface of the plate element
\( A_t \) area of the top surface of the tether
\( d \) width of a cantilever beam
\( E \) Young’s modulus of silicon (\( \sim 160 \text{ GPa} \))
\( f \) resultant fluid shear force acting on the top surface of a single tether
\( F_y \) resultant fluid normal force acting on the top surface of 1/4 of the plate element
\( F_z \) resultant fluid shear force acting on the top surface of 1/4 of the plate element
\( h \) thickness of a cantilever beam
\( I_{yy}, I_{zz} \) area moment of inertia of the tether’s cross-section
\( l \) length of a cantilever beam
\( L \) length of the tether
\( M_y, M_z \) bending moment at the root of the tether
\( N, p \) dopant concentration
\( P \) piezoresistance factor
\( t \) thickness of the tether
\( T \) temperature
\( w \) width of the tether
\( y, z \) 1/2 of the tether’s thickness or width

Greek letters
\( \pi_l \) longitudinal piezoresistance coefficient
\( \rho \) resistivity of the piezoresistor
\( \sigma_{xx} \) bending stress at the root of the tether

2. Design and theory

2.1. Sensor design

The floating element sensor concept [1,5–7] consists of a plate element suspended by four tethers (Fig. 1). Capacitive and optical transduction schemes have been integrated with this geometry in the past to measure shear stress directly [1,6,7]. However, they are difficult to use and limited by turbidity for water applications. However, our design uses a transduction scheme of sidewall-implanted piezoresistors [11] measuring lateral force (integrated shear stress), along with traditional top-implanted piezoresistors detecting normal forces. Piezoresistors are placed at the root of each tether. The orientations of the piezoresistors are such that two are sensitive to lateral deflections in the flow direction, while two are sensitive to out-of-plane deflections. As fluid flows over the top surface of the sensor, it exerts shear stress on the plate element and tethers, causing the tethers to bend. Shear stress is inferred from deflection and stress in the tethers. Each sensor measures normal and lateral forces simultaneously.

Arrays of various sensor designs were designed and fabricated to evaluate parametric effects at the microscale, including: dimensions of the tethers (lengths of 264–1236 \( \mu \text{m} \), widths of 7–15 \( \mu \text{m} \), and thickness of 7–12 \( \mu \text{m} \)), plates (40–1030 \( \mu \text{m} \) square), and their ratios (0.1–5); gap sizes (5–20 \( \mu \text{m} \)); 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 underwater sensors at low Reynolds numbers is not known, thus gap size effects will be studied.

2.2. Beam mechanics

Each tether is 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. Eqs. (1a) and (1b) show bending moments due to the resultant fluid forces. Each tether acts as a spring and the sensor is modeled as four springs in parallel. An equivalent in-plane spring constant of the sensor, \( k_s \), is shown in Eq. (1c).

The stress at the root of the tether where the piezoresistor is located can be calculated (Eqs. (2a) and (2b)), and the change in the resistance of the piezoresistor due to the applied stress may be predicted (Eq. (3)). The piezoresistors are oriented along the \( \langle 110 \rangle \) direction of (1 0 0) p-type silicon, which gives the maximum value for \( \pi_l (\sim 71 \times 10^{-12} \text{ cm}^2 \text{ dyne}^{-1}) \) [14]. However, this value needs to be adjusted to take into account the dependence of \( \pi_l \) on doping concentrations in the piezoresistors.

\[
M_{\text{guided-end}} = \frac{FL}{2} + \frac{fL^2}{6} \quad (1a)
\]
\[
M_{\text{fixed-end}} = \frac{FL}{2} + \frac{fL^2}{3} \quad (1b)
\]
\[
k_s = \frac{96EI_{yy}(A_p/4 + A_t)}{L^3(A_p/2 + A_t)} \quad (1c)
\]
The electronic states of a material depend on internal atomic structure and electron motions in a given crystal orientation. In a crystalline material, these states form quasi-continua in energy called energy bands. This internal atomic arrangement and energy bands can be altered by applying stress (or strain) and tilting, respectively. Gaussian implant profiles and damage caused during ion implantation are incorporated in the simulation. The ion implantation simulation considers amorphization, silicon atoms knocked out of lattice sites, interstitials produced when silicon atoms are displaced by implanted ions, and point defect recombination. The TSUPREM-4 “Full Method” of diffusion is chosen to simulate damage due to ion implantation and oxidation enhanced diffusion. Resulting parameters of interest include material layers, metallurgical junction, electrical properties, such as sheet resistance, and plots of the dopant profiles/distributions. We solve for these parameters at three times: after ion implantation, after rapid thermal anneal (RTA), and after oxidation of the aluminum/silicon passivation layer.

The simulated dopant profile is shown in Fig. 3. The peak doping concentration for the nominal dose of \(4 \times 10^{15} \text{ cm}^{-2}\) is about \(6.5 \times 10^{18} \text{ cm}^{-3}\). According to Harley’s fit of the experimental data in the literature (Eq. (4)), this doping concentration corresponds to \(P(p) = 0.68\) and an adjusted \(\pi_1\) of about \(49 \times 10^{-11} \text{ Pa}^{-1}\). Using the adjusted \(\pi_1\) value and equations of beam mechanics (Eqs. (1)–(3)), typical in-plane shear stress sensitivity of the sidewall piezoresistor is predicted to be 0.068 mV Pa\(^{-1}\) with bias voltage of 10 V in a Wheatstone bridge configuration and before amplification.

3. Fabrication

The fabrication process (Fig. 4) starts with 4 in. n-type (Ph-doped) double-polished (1 0 0) SOI wafers. The typical resistivity of the device layer is about 18 Ω cm. The device layer thickness ranges from 7 to 12 μm and determines the thickness of the tethers and the plate element (with 10 μm as the nominal design). The handle layer and the buried oxide thicknesses are 300 and 0.5 μm, respectively.

Alignment marks are patterned on the wafers. Next, 250 Å of thermal oxide is grown at 850 °C for 13 min. This screening oxide is intended to minimize ion-implant damage of the silicon lattice. Ion implantation forms the top piezoresistors and the using Harley’s piezoresistance factor, \(P(p)\), for our higher concentrations.

\[
P(p) = \log \left( \frac{b}{p} \right)^a
\]  

We use TSUPREM-4 simulation to find the dopant profile, and then adjust \(\pi_1\) accordingly. TSUPREM-4 [20] is a computer program that simulates the processing steps used in the manufacture of silicon integrated circuits (ICs) or MEMS devices, e.g. ion implantation, oxidation/diffusion, and etching processes during the fabrication of the piezoresistors. Our one-dimensional simulation in the direction normal to the silicon surface used a depth of analysis equal to our maximum plate thickness, 12 μm, with spacing interpolation from top to bottom. A denser grid is created near the wafer surface to yield more precise information in the area of steep dopant profiles. Simulated parameters of (1 0 0) wafer orientation, phosphorous background dopant, and initial resistivity of 18 Ω cm represent actual properties of our silicon-on-insulator (SOI) device layer. The parameters include: dose of \(1 \times 10^{15} \text{ cm}^{-2}\), 50 keV, and 70° C for dose, energy, and tilt angle, respectively. Gaussian implant profiles and damage caused during ion implantation are incorporated in the simulation. The ion implantation simulation considers amorphization, silicon atoms knocked out of lattice sites, interstitials produced when silicon atoms are displaced by implanted ions, and point defect recombination. The TSUPREM-4 “Full Method” of diffusion is chosen to simulate damage due to ion implantation and oxidation enhanced diffusion. Resulting parameters of interests include material layers, metallurgical junction, electrical properties, such as sheet resistance, and plots of the dopant profiles/distributions. We solve for these parameters at three times: after ion implantation, after rapid thermal anneal (RTA), and after oxidation of the aluminum/silicon passivation layer.

The simulated dopant profile is shown in Fig. 3. The peak doping concentration for the nominal dose of \(4 \times 10^{15} \text{ cm}^{-2}\) is about \(6.5 \times 10^{18} \text{ cm}^{-3}\). According to Harley’s fit of the experimental data in the literature (Eq. (4)), this doping concentration corresponds to \(P(p) = 0.68\) and an adjusted \(\pi_1\) of about \(49 \times 10^{-11} \text{ Pa}^{-1}\). Using the adjusted \(\pi_1\) value and equations of beam mechanics (Eqs. (1)–(3)), typical in-plane shear stress sensitivity of the sidewall piezoresistor is predicted to be 0.068 mV Pa\(^{-1}\) with bias voltage of 10 V in a Wheatstone bridge configuration and before amplification.
conducting regions. Both implants (Boron) are done at 50 keV and 7° angle from the normal axis to minimize channeling. The top piezoresistor dose is 1 × 10^{15} cm^{-2} and the conducting region dose is 1 × 10^{16} cm^{-2}. Both implants are annealed using an RTA process at 1050 °C for 75 s. Then, the screening oxide is etched away using 34% NH₄F, 7% HF, and 59% water, i.e. 6:1 buffered oxide etch (BOE). About 1.1 μm of low temperature oxide (LTO) is deposited at 400 °C in preparation of the sidewall-implant. LTO and silicon are 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. The wafers are hydrogen annealed at 1000 °C and 10 mTorr for 5 min [21] to smooth the sidewall from the resulting scallops due to DRIE process. Fig. 5 shows the sidewall roughness before and after the hydrogen anneal. The top surface is then covered with photoresist and an opening near the root of each tether is patterned to allow for an angled ion implant at 20° from the normal axis. Boron, with dose of 4 × 10^{15} cm^{-2}, is implanted at 40 keV. After stripping the photoresist with 90% concentrated H₂SO₄ and 10% H₂O₂ and removing the LTO using 6:1 BOE, the sidewall-implant is annealed using an RTA process at 1050 °C for 75 s. A passivation oxide of 2100 Å is thermally grown at 1000 °C for 30 min, followed by a post-oxidation inert anneal for 5 min. Next, the passivation oxide is patterned and etched using 6:1 BOE to open an electrical connection for aluminum to the conducting region. One micron of 99%–aluminum/1%–silicon is sputtered, patterned, and etched using aluminum etch (72% phosphoric acid, 3% acetic acid, 3% nitric acid, and 12% water). The sensors are then released from the backside using a DRIE process to etch the handle layer silicon, while the buried oxide is removed by 6:1 BOE. Finally, the wafers are treated to a forming gas (hydrogen and nitrogen) anneal at 400 °C for 2 h to reduce trapped charges due to incompletely oxidized atoms close to the Si–SiO₂ interface [22]. Fig. 6 shows scanning electron microscopy (SEM) images of the released sensors.

4. Characterization and results

4.1. In-plane calibration

A nominal design sensor (500-μm floating element size, 10-μm tether width and thickness) is calibrated in the lateral direction using a microfabricated piezoresistive 15 μm-thick silicon cantilever force sensor (Fig. 7a). The force sensor applies lateral load to the shear stress sensor. The equivalent spring constant of the force sensor, \( k_c \), is calculated from beam theory (Eq. (5)) to be 0.25 N m^{-1}. Cantilever force sensitivity (~4.57 kV N^{-1} with 200× bridge output amplification) is subsequently calibrated using a laser Doppler vibrometer (LDV, Polytec OFV3001) and resonance excitation techniques. Details of the force sensor and its calibration method were reported elsewhere [23,24].

\[
k_c = \frac{E d h^3}{4 l^3}
\]

(5)

The cantilever is mounted on a piezoactuator stage with the tip pointing down, while the sensor is mounted on a glass slide on top of an inverted microscope and oriented perpendicular to the cantilever (Fig. 7b). The tip of the cantilever is inserted from the top into the gap of one of the sensors with larger gap size, 20 μm (Fig. 7c). The image in Fig. 7c is 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 is 500 μm × 500 μm.

The cantilever is then moved toward the plate element by a piezoactuator (PHera P622.Z) with control electronics (E-505) in increments of 1 μm from 0 to 200 μm. The cantilever pushes against the shear sensor plate element. The shear sensor is ~210 times stiffer than the cantilever (\( k_s \gg k_c \)). Conceptually, we model this as two springs in series (Fig. 8). Thus if we assume a 200-μm total displacement of the base of the cantilever, 99.53% of deflection is accommodated by the force sensing cantilever. The uncertainty in our applied force due to uncertainty in deflection is less than 0.5% full scale. Therefore, the applied displacement is assumed to be accommodated completely by deflection of the cantilever and moving the cantilever a known distance then applies a well-characterized force to the shear sensor in the in-plane direction. However, uncertainty in applied force due to uncertainty in \( k_c \) is 11.2%. Some error due to torsion of the cantilever is
Fig. 4. Fabrication starts with SOI wafer (a). Top piezoresistors defined by boron implants (b, c, A). Deposition of LTO (d). Sensors defined by deep reactive etch (DRIE) of trenches, silicon hydrogen anneal and sidewall implant comes after trench etch (e, f, B). LTO was stripped and passivation oxide was thermally grown, patterned, and etched (g). Aluminum interconnects patterned (h, C). Sensors released by backside DRIE (i, D).

Fig. 5. Sidewall roughness before hydrogen anneal (left) and after (right).
noted at the onset of loading 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. Sensitivity to shear stress is then inferred from data as shown in Fig. 9. The elapsed time for each 1 μm piezoactuator step is 0.5 s. Data are taken over the last 0.1 s at 2400 Hz and averaged to give a single data point for each piezoactuator step to reduce the effect of ringing. The large noise component is likely due to low mechanical stiffness in the experimental setup, slippage of the cantilever to plate contact during the test and uncontrolled light and electromagnetic noise sources during the tests. This particular sensor has an in-plane force sensitivity of about 50 mV μN⁻¹. The crosstalk of the top-implant piezoresistor to in-plane force is also quite low, about 0.8 mV μN⁻¹, confirming low sensitivity to off-axis loads.

![Fig. 6. SEM image of the whole sensor, 500-μm plate element (left). SEM image of the sidewall-implanted piezoresistor on a 15-μm wide tether (right).](image)

![Fig. 7. (a) Microfabricated piezoresistive silicon cantilever force sensor. The length (l), width (b), and the thickness (h) of the cantilever were 6000, 400, 15 μm, respectively. (b) Experimental setup. (c) 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.](image)

![Fig. 8. Lumped-parameter model of the experimental setup. x_input is the piezoelectric-based actuator input displacement.](image)

![Fig. 9. Typical sensitivity plot. In-plane and out-of-plane sensitivities to in-plane motion (based on the slopes) are 50.3 mV μN⁻¹ (0.063 mV Pa⁻¹) and 0.8 mV μN⁻¹ (0.001 mV Pa⁻¹), respectively.](image)
Fig. 10. Some hysteresis and non-linearity in the measurements is apparent in this load/unload data.

Fig. 10 shows the typical hysteresis and non-linearity of the measurements over the piezoelectric-based actuator displacement range. Fig. 11 shows the trendlines and repeatability of five sequential measurements of shear sensor output. The trendlines are generated based on the data from 50 to 150 μm of piezoactuator displacement. This is 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 assumptions of the cantilever at large deflections. The average sensitivity of the shear sensor to input displacement is 0.0101 V μm⁻¹ with a standard error of slope of 0.0022 V μm⁻¹. Therefore, the in-plane force sensitivity of the sidewall piezoresistor translates to 0.052 ± 0.011 mV Pa⁻¹ (before amplification). The theoretical value is found from beam mechanics and piezoresistance equations with the adjusted $\pi_1$ value (Eqs. (1)–(3)). The predicted sensitivity is 0.068 mV Pa⁻¹.

4.2. Sensitivity analysis

We also use TSUPREM-4 simulations to investigate the effect of fabrication process tolerance on the discrepancy between the theoretical and experimental values for the in-plane sensitivity. The ion implantation simulations are done by varying the dose ($1 \times 10^{15} - 7 \times 10^{15}$ cm⁻²), energy (40–60 keV), and the tilt angle (40–60°) from the normal axis of silicon surface. These are worst case variations of the default values of $1 \times 10^{15}$ cm⁻², 50 keV, and 70° for dose, energy, and tilt angle, respectively. The dopant profiles after ion implantation, after RTA anneal, and after oxidation of the aluminum/silicon passivation layer are plotted again. Fig. 12 summarizes results of the simulations after oxidation of the aluminum/silicon passivation layer (final diffusion process). We conclude that variations in implant dose would contribute the most offset in peak doping concentration, and thus the targeted sheet resistance $R_{sh}$ (up to 150%) and sensitivity (up to 16%). Table 1 shows the range of $P(p)$ variations with respect to input parameters of tilt angle, energy, and dose.

The sensitivity of the sidewall-implant could also be affected by dimensional variations due to other fabrication process errors, such as imperfection in lithography and etching (±1 μm), and wafers specifications tolerance. The device layer thickness,
which defines the thickness of the plate element and the tethers, was quoted by the manufacturer to have ±1 μm tolerance. Table 2 shows the contribution of dimensional variations to the normalized change in resistance. Note that the normalized change in resistance is inversely proportional to the thickness and square of the width, while linearly proportional to the length of the tether for in-plane deflection of the tethers.

Theoretical calculations and experiments have been done in the past to determine the Young’s modulus (\(E\)) and other mechanical properties, e.g. Poisson’s ratio, elasticity constants, and hardness of silicon [25–28] for various crystal orientations. Young’s modulus of 160 GPa for [1 1 0] direction in a (1 0 0) silicon wafer, was used in the calculation of the predicted sensitivity. Given our process tolerances (Table 2) and discrepancies in reported values of \(E\) (measured and calculated vary by upwards of 10%), the resulting uncertainty on \(k_s\) is 18.85%, which is in the order of other sources of variations in the experiment. For example, Bhushan and Li [27] extracted estimates of moduli for bulk undoped silicon ranging from 179 to 202 GPa and as low as 62 GPa for heavily doped p⁺-type silicon. Eq. (6) [29] is used to calculate for uncertainty in \(k_s\), where \(R, x, \) and \(w\) represent \(k_s\), the independent variables, and uncertainties in the independent variables, respectively.

\[
w_R = \left[ \frac{\partial R}{\partial x_1} w_1 \right]^2 + \left[ \frac{\partial R}{\partial x_2} w_2 \right]^2 + \cdots + \left[ \frac{\partial R}{\partial x_n} w_n \right]^2 \right]^{1/2} \tag{6}
\]

The in-plane force sensitivity of the sidewall-implant was predicted to be 0.068 mV Pa⁻¹, while the experimental sensitivity ranges from 0.041 to 0.063 mV Pa⁻¹ (60–93% of the theoretical prediction). The lower experimental values are due to a combination of two or more sources of variations as shown in Tables 1 and 2.

### 4.3. Dynamic analysis

The sensor is mounted on a microscope slide and driven in out-of-plane motion by a Jodon EV-30 piezoelectric shaker. The shaker is driven by a 25 mV white noise input with frequency ranging from 500 Hz to 50 kHz, amplified at fixed gain of 100× by a Krohn-Hite 7500 Widebands Power Amplifier. A Polytec OFV3001 laser Doppler vibrometer is used to extract the average out-of-plane velocity of the plate element. The LDV output is connected to an HP89441A vector signal analyzer and its velocity filter is set to 5 mm s⁻¹. The frequency spectra on the analyzer show peaks of the modes of vibration. The first resonant frequency is experimentally found to be ∼19 kHz. A FEMLAB simulation, including the oxide thin film on top of the silicon (but not internal stress), is used to verify the result. From FEMLAB, the first resonant frequency is found to be 13.4 kHz, lower than predicted. Saif [30] has shown that the transverse stiffness, and therefore the resonant frequency, of a beam structure is also dependent on the compressive force acting on it. The square of the resonant frequency of the system decreases linearly with the compressive force acting on the beam before buckling, but increases linearly after buckling when the oscillation is about the buckled equilibrium states. However, our geometry includes an unbalanced compressive force (Fig. 13) and possibly an induced curvature of the sensor. Driving the sensor at resonance would then be expected to produce a one-sided artifact due to the unbalanced energy transfer, as observed in Fig. 14.

#### 4.4. Out-of-plane calibration

The sensitivity of the top-implanted piezoresistor to normal force is characterized using the previously reported benchtop calibration technique [24] and the same setup as dynamic calibration, except that the sensor is driven in out-of-plane motion at its resonant frequency of 18.2 kHz. Both signals from the LDV and the conditioned output of the Wheatstone bridge (which is amplified 1000× using AD624) are captured using an HP 54542A Oscilloscope (Fig. 14). The sensor sensitivity is found to be about 0.04 mV Pa⁻¹ without amplification. The effect of hydrogen annealing, which introduces more diffusion of dopant as well as silicon reflow on the surface after top piezoresistor implant may be the cause of this decrease in sensitivity. TSUPREM-4 does not account for reflow of silicon atoms on surfaces and hydrogen-enhanced diffusion. This effect is still under investigation.

### Table 1

<table>
<thead>
<tr>
<th>Input range</th>
<th>Peak concentration range (cm⁻³)</th>
<th>(P(\rho)) range</th>
<th>Sensitivity range (mV Pa⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt angle (40–60°)</td>
<td>(2.75 \times 10^{19}–1 \times 10^{19})</td>
<td>0.64–0.75</td>
<td>0.064–0.075</td>
</tr>
<tr>
<td>Energy (40–60 keV)</td>
<td>(6.0 \times 10^{18}–6.5 \times 10^{18})</td>
<td>~0.68</td>
<td>~0.068</td>
</tr>
<tr>
<td>Dose (1 × 10²³–7 × 10²³ cm⁻²)</td>
<td>(1.75 \times 10^{19}–1.25 \times 10^{19})</td>
<td>0.62–0.79</td>
<td>0.062–0.079</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Dimension (nominal value)</th>
<th>Change in (\Delta \rho \rho)</th>
<th>Sensitivity (mV Pa⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, 500 μm ± 1 μm</td>
<td>±0.2%</td>
<td>~0.068</td>
</tr>
<tr>
<td>Width, 10 μm ± 1 μm</td>
<td>−18% to +23%</td>
<td>0.056–0.084</td>
</tr>
<tr>
<td>Thickness, 10 μm ± 1 μm</td>
<td>−10% to +11%</td>
<td>0.062–0.076</td>
</tr>
</tbody>
</table>
Fig. 14. Response curves from the Vibrometer and the top-implanted piezoresistor to normal force. The sensitivity is \( \sim 40 \text{ mV Pa}^{-1} \). The two curves have 90° phase shift and are proportional to plate velocity and strain at the root of the tether. Examples of the artifacts suspected due to unbalanced oxide stresses are shown by the circles.

4.5. Temperature coefficient of sensitivity

Piezoresistors are sensitive to electromagnetic noise and temperature. A simple experiment is set up to characterize the sensitivity of the piezoresistor with respect to change in temperature. The sensor is submerged in a deionized water bath (in a beaker) and enclosed in a grounded box to minimize contribution of electromagnetic interference to change in resistance. The temperature of the water bath is monitored using a thermometer with a resolution of 0.5 °C. The bath is slowly heated using a hotplate to 50 °C and cooled down by adding ice to about 10 °C. The change in resistance is monitored using a HP34401A digital multi meter (DMM). Fig. 15 shows the change in resistance with respect to change in temperature for three different heat and cool cycles. The temperature coefficient of sensitivity is found to be 0.0081 kΩ °C\(^{-1}\), which translates to about 30 Pa °C\(^{-1}\). Therefore, temperature compensating signal conditioning will be used for underwater measurements.

Fig. 15. 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\(^{-1}\).

4.6. Noise characterization

The noise measurements are done using a Stanford Research Systems SR570 current preamplifier to extract the noise spectra of the piezoresistors. The SR570 sets current through the piezoresistor and converts this current to a voltage read by an HP89441A vector signal analyzer. The HP89441A measures the noise measurements were done using Stanford Research Systems SR570 current preamplifier. Roll-off above 10\(^4\) Hz is due to low-pass filtering in the low-noise mode operation of SR570.

Fig. 16. Diagram of noise measurement setup.

Fig. 17. The noise measurements were done using Stanford Research Systems SR570 current preamplifier. Roll-off above 10\(^4\) Hz is due to low-pass filtering in the low-noise mode operation of SR570.
power spectral density per decade. Fig. 16 shows the diagram of the setup. During the experiment, the sensor is encapsulated by grounded box to avoid noise contributions due to electromagnetic interference. Fig. 17 shows almost an order of magnitude improvement on the 1/f noise level of the sidewall-implanted piezoresistors before and after hydrogen anneal. The integrated noise level over bandwidth of interest (1 Hz–10 kHz) is reduced to 0.16 μV (after H2 anneal) from 2.63 μV (before H2 anneal). This supports reports that surface quality plays a role in the 1/f noise level in ion-implanted piezoresistors [31].

5. Conclusion

A piezoresistive MEMS shear stress sensor for underwater applications has been designed, fabricated, and characterized. The design was based on the floating-element concept, a direct method of shear stress measurement. Novel fabrication techniques included oblique-implant of piezoresistors and a hydrogen anneal step to smooth scalloped silicon surface resulting from a DRIE process. We characterized out-of-plane and in-plane force sensitivities, temperature coefficient of sensitivity, dynamics, and noise in piezoresistors. TSUPREM-4 simulations have been done to investigate discrepancies between predicted and experimental in-plane force (shear stress) sensitivities.

6. Future work

Further characterization and underwater testing of the devices is underway. Arrays of devices with temperature compensation, amplification, and multiplexing will be utilized in underwater experiments. Improvements of the design of the sensors and electrical through-wafer interconnects are planned in future designs to obtain the desired reliability.

Acknowledgments

This work was supported under NSF award CTS-0428889. Fabrication work was performed in part at the Stanford Nanofabrication Facility (a member of the National Nanotechnology Infrastructure Network) which is supported by the National Science Foundation under Grant ECS-9731293, its lab members, and the industrial members of the Stanford Center for Integrated Systems. A special thanks to Prof. Stephen Monismith, Prof. Jeff Koseff, and Dr. Matt Reidenbach for design input on measurements for a coral reef environment. VM would like to thank Stanford Graduate Fellowship. The authors would also like to thank members of Stanford Microsystems Laboratory.

References

Biographies

A. Alvin Barlian is currently pursuing his doctoral degree in the mechanical engineering department at Stanford University. His doctoral research focuses on design, fabrication, and testing of piezoresistive MEMS underwater shear stress sensors for environmental and biomedical applications. In addition, he is also working on sensitivity characterization of microfabricated piezoresistive cantilevers for biological applications. His other academic interests include bio-MEMS, nanoscale science, fuel cell technology, and fluid mechanics. He received his B.S. degree in Mechanical Engineering from Purdue University with Honors (2001) and his M.S. in Mechanical Engineering from Stanford University (2003). He was a PT Caltex Pacific Indonesia Scholar from 1998 to 2002.

Sung-Jin Park received his B.S. and M.S. degrees in Mechanical Engineering in 1999 and 2003 with Honors, from Seoul National University (SNU), Seoul, Korea. He is currently pursuing his Ph.D. degree in Mechanical Engineering at Stanford University, Stanford, CA. He did his M.S. thesis on modeling, design, and fabrication of microfluidic device, which won the best thesis award from SNU. His doctoral research focuses on mechanotransduction mechanism of touch sensation with microfabricated piezoresistive cantilever indentation system. His interests include mechanotransduction mechanism of cell and biosystem and the modeling, design and control of MEMS for biological applications. He received the Samsung Lee Kun Hee Scholarship from 2003 to 2006.

Vikram Mukundan is a doctoral candidate in the mechanical engineering department at Stanford University. His research focuses on design and fabrication of microscale sensors and actuators for measuring biomechanics in cells. His research interests include bio-MEMS, micro/nano-scale technology and its applications to biosciences. He received his B.Tech. degree in Mechanical Engineering from Indian Institute of Technology, Madras (2003) and his M.S. in Mechanical Engineering from Stanford University (2005). He is a recipient of the Stanford Graduate Fellowship from 2003-06.

Beth L. Pruitt received her PhD in 2002 from Stanford University for work on Piezoresistive Cantilevers for Characterizing Thin-Film Gold Electrical Contacts. She then joined the Laboratory for Microsystems and Nanoengineering at the Swiss Federal Institute of Technology (EPFL) where she worked on nanostencils and polymer MEMS. She joined the Mechanical Engineering faculty of Stanford in Fall 2003 and set up the Stanford Microsystems Lab. Her research includes the development of novel processes and micromachined sensors and actuators for measuring micro-mechanical behavior, especially that of soft condensed matter, as well as the analysis, design, and control of integrated electro-mechanical systems. She is particularly interested in the biomedical applications of nanofabricated devices with the goal of developing integrated MEMS-biological test platforms, precise measurement and analysis systems, and reliable manufacture methods. This research includes instrumenting and interfacing devices between the micro and macro scale, understanding the scaling properties of physical and material processes and finding ways to reproduce and propagate new technologies efficiently and repeatedly at the macro-scale. Prior to her Ph.D. at Stanford, Beth Pruitt was an officer in the U.S. Navy. She served a first tour as a project manager at the engineering headquarters for U.S. Navy nuclear program supervising submarine reactor fuel removal and refueling projects including: oversight of project schedules, manpower, training, and budgets; engineering review of equipment mechanical designs; and evaluation of technical procedures. Her second tour was as a Systems Engineering instructor at the U.S. Naval Academy, where she also taught offshore sailing.