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Design and characterization of microfabricated piezoresistive floating element-based 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. 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.

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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 (∼160 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

π_l	longitudinal piezoresistance coefficient
ρ	resistivity of the piezoresistor
σ_{xx}	bending stress at the root of the tether

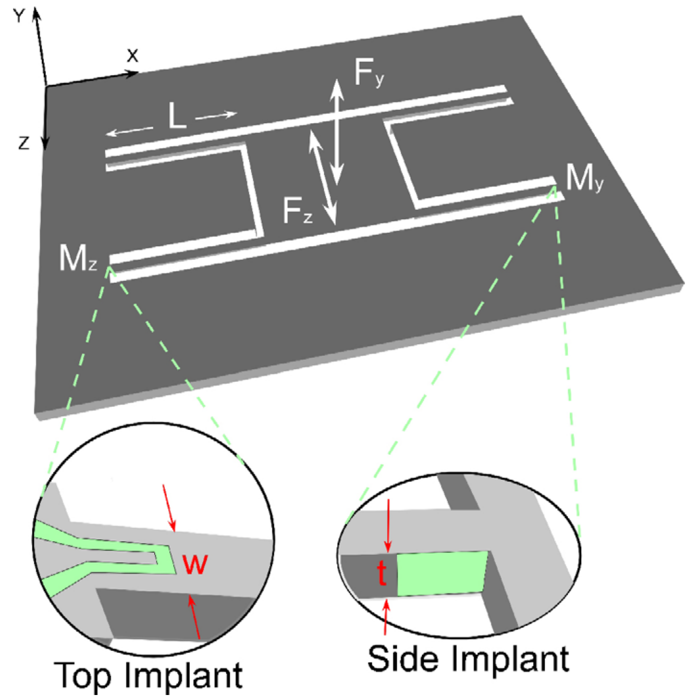

Fig. 1. Piezoresistive floating-element shear stress sensor.

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 μm, widths of 7–15 μm, and thickness of 7–12 μm), 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 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 ⟨1 1 0⟩ direction of (1 0 0) p-type silicon, which gives the maximum value for π_l (∼71 × 10^{-12} cm^2 dyne^{-1}) [14]. However, this value needs to be adjusted to take into account the dependence of π_l on doping concentrations in the piezoresistors.

$$M_{\text{guided-end}} = \frac{FL}{2} + \frac{fL^2}{6} \tag{1a}$$

$$M_{\text{fixed-end}} = \frac{FL}{2} + \frac{fL^2}{3} \tag{1b}$$

$$k_s = \frac{96EI_{yy}(A_p/4 + A_t)}{L^3(A_p/2 + A_t)} \tag{1c}$$