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# Fabrication of an in-plane SU-8 cantilever with integrated strain gauge for wall shear stress measurements in fluid flows

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**Abstract**

We present a cantilever fabricated from the polymer SU-8 for the measurement of wall shear stress in fluid flows. The pressure-induced deflection of the cantilever, measured using an calibrated and integrated nichrome strain gauge, can be related to the wall shear stress on the surface. The initial degree of curvature of the cantilever can be controlled via the exposure dose, which allows a small positive deflection to be achieved, and so minimises the intrusion into the flow. Wind tunnel testing results show a sensitivity greater than 2.5 mV/Pa, with a shear stress of 0.38 Pa and excitation of 1V.

*Keywords*: strain gauge; SU-8; shear stress; cantilever;

## 1. Introduction

Existing devices for shear stress measurement include hot film anemometers, Preston tubes, floating element sensors, indirect optical sensors and surface fences, as well as techniques such as oil film interferometry and the use of liquid crystal coatings. Macro-scale versions of many devices have been limited due to the trade-off between sensor spatial resolution and the ability to measure small forces.

At the MEMS scale, a surface fence can be used to measure the static pressure drop between the upstream and downstream sides of the fence, which can then be related to the shear stress by calibration[1]. This technique was developed to incorporate a piezoresistor into a silicon fence[2]. An alternative to this fence design is the artificial haircell, based on a biological mechanoreceptor. This is effectively a cantilever projecting vertically from the surface with an integrated resistive strain gauge at the base[3].

It is important that any wall shear measurement device is confined immediately adjacent to the wall, and so projecting out from the wall at a right angle would necessitate a very short cantilever.

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## 2. Sensor design

The sensor presented here consists of an in-plane SU-8 cantilever with a nichrome strain gauge on the underside. The low piezoresistive gauge factor of nichrome combined with the low Young's Modulus of SU-8 provides a combination with similar sensitivity to a silicon device with a doped piezoresistor[4]. At the root of the cantilever is the main body of the device, which contains a Wheatstone bridge and four contact pads.

Cantilevers were tested which were 2, 3 or 4 mm long, 400 or 600 µm wide and 12 µm thick. The nichrome resistor for each cantilever was 125 nm thick and consisted of a meander resistor with a total length of 12.65 mm and width of 40 µm, producing a typical resistance of 5 kΩ. For the longer cantilevers, metal was extended the full length of the cantilever in order to maintain the stress interaction along this dimension; however the extended section was not connected electrically. The operation of the cantilever sensor in an airflow is shown in Fig. 1. The nichrome provided a gauge factor of 2.2 and a low temperature coefficient of resistivity (TCR ~150 ppm/°C), minimising the heating effects on the output voltage.

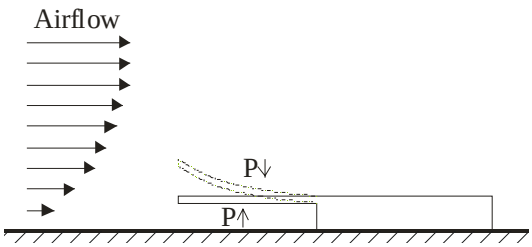



Fig. 1. Schematic of cantilever sensor in airflow.

## 3. Fabrication and Control of Cantilever Curvature

The fabrication process for the cantilevers is shown in Fig. 2, with a completed device in Fig. 3. The devices are made on a silicon substrate and released after fabrication. The release layer for the devices was ProLIFT, from Brewer Science, with a thin adhesion film of titanium deposited over the ProLIFT layer.

Due to the stress gradient formed in the SU-8 layer when the polymer cross-links, the cantilevers were found to deflect out of plane. This deflection can be either positive or negative depending on the process conditions. A number of factors were found to influence the degree of stress gradient, including the exposure dose. The stress gradient can be calculated from the tip deflection of the cantilever[5], using the equation

$$\frac{\Delta\sigma}{\Delta t} = \frac{E}{1-\nu}\frac{2}{L^2}\delta$$

where $E$ is Young's modulus, $\nu$ is Poisson's ratio, $\sigma$ is the stress, and $t$, $L$ and $\delta$ are respectively the thickness, length and tip deflection of the cantilever.

Devices were fabricated using a range of exposure doses, and the tip deflection of the released and inverted cantilever was then measured, with an upward deflection defined as positive. The stress gradient was then calculated, as shown in Fig. 4. All processing was as shown in Fig. 2 with the omission of step (d), i.e. without the NiCr resistor. At low exposure doses the effect of the UV exposure was found to dominate. SU-8 shrinks on cross-linking, and so where the acid generation is greatest, closest to the UV light, the SU-8 is more fully cross-linked, causing the cantilevers to deflect away from the substrate (a negative deflection). The positive curvature of the

cantilever at higher exposure doses is attributed to the temperature difference between the top and bottom of the layer during the post-exposure bake and also the silicon/SU-8 interface, with the thermal effect dominating.

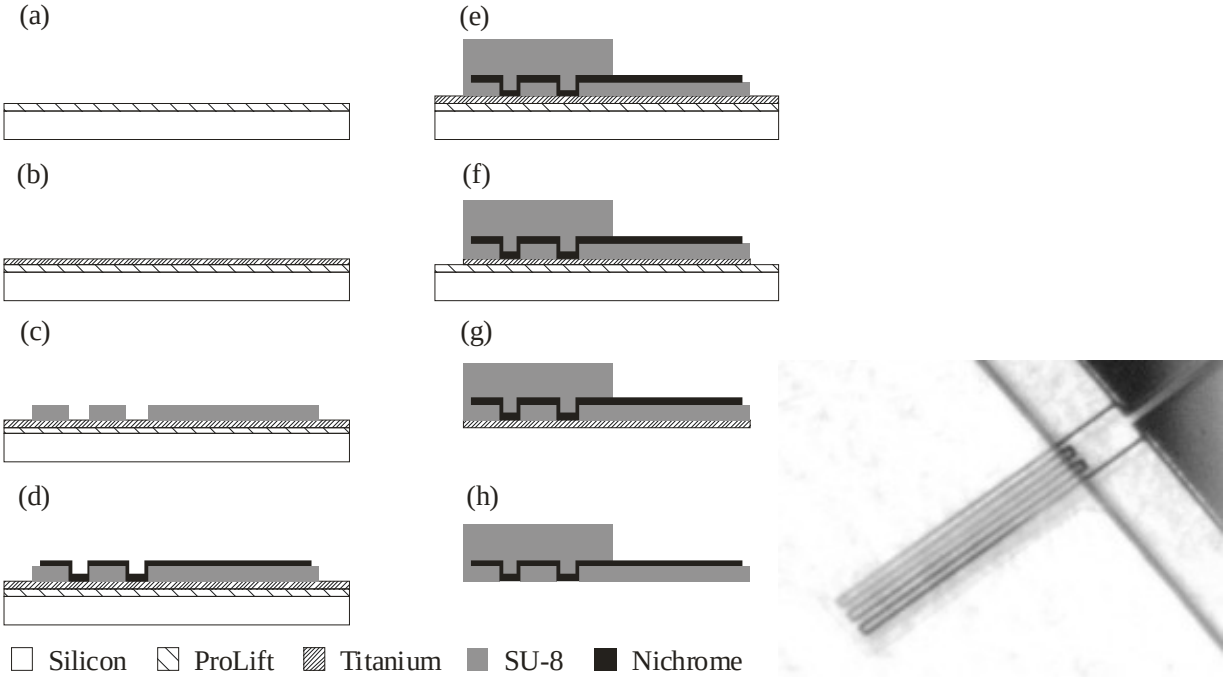



Fig. 2 (left). Fabrication process. a) Spin coat a layer of ProLIFT on a silicon substrate. b) Sputter coat with 50 nm of titanium. c) Spin coat and pattern 12 µm of SU-8 10. d) Sputter coat and pattern 125 nm of nichrome. e) Spin coat and pattern a 100 µm layer of SU-8 50. f) Etch the exposed Ti layer in HF. g) Remove the ProLIFT in TMAH to release the cantilevers. h) Remove the remaining titanium in HF. Fig. 3 (right) a close-up of the sensor element.

Control of the exposure dose allowed positive or negative tip deflections to be achieved, despite the stress in the nichrome layer also affecting the bend of the cantilever. A slightly positive initial tip deflection of around 50 µm was selected for all measurements.

## 4. Experimental results

The cantilevers were mechanically tested, allowing the force, deflection and resistance to be measured. A needle placed at the tip of the cantilever was displaced in a series of steps and the force applied on the cantilever and the strain gauge resistance was measured. For a 2 mm long and 400 µm wide cantilever, the change in voltage output from the Wheatstone bridge was $9.6 \times 10^{-4}$ (mV/V)/µm of tip deflection, as shown in Fig. 5.

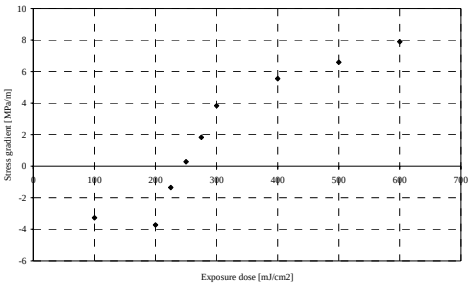
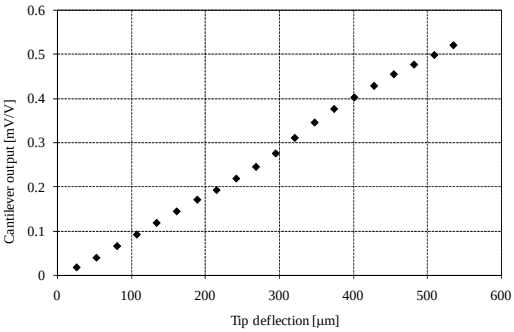



Fig. 4. Stress gradient as a function of exposure dose for a 12 µm thick cantilever.



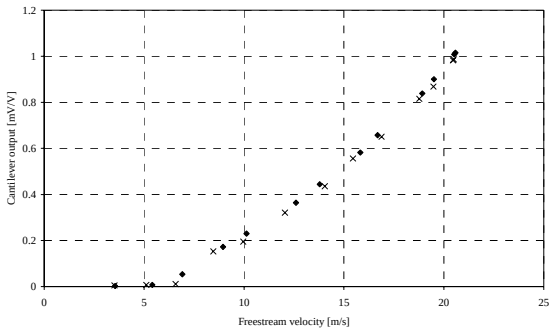




Fig. 5 (left). Response of 2 mm × 600 µm cantilever sensor for varying tip deflection. Fig. 6 (right). Responses of two cantilevers on a flat plate in the wind tunnel.

Cantilevers were mounted on a flat plate in a wind tunnel at an axial position 0.25 m downstream from the leading edge. An excitation voltage of 1 V was applied to the Wheatstone bridge. The sensors' response, as a function of freestream air velocity, is shown in Fig. 6. At ~20 m/s and wall shear stress of 0.38 Pa (measured using a Preston tube) a response of approximately 1 mV/V was seen. Longer cantilevers had a greater response for the same shear stress. Different cantilevers of the same design showed very similar results, demonstrating good repeatability.

## 5. Conclusions

A cantilever fabricated from SU-8 with an integrated nichrome strain gauge has been shown to be suitable for the measurement of wall shear stress. Both the initial and the stress differential induced cantilever curvature can be controlled via the exposure dose, allowing a small positive deflection to be achieved and so minimising the intrusion into the flow. Mechanical and wind tunnel testing showed a response of $9.6 \times 10^{-4}$ (mV/V)/µm and 1 mV/V for a freestream velocity of 20 m/s (a shear stress of 0.38 Pa) respectively, equivalent to a sensitivity of 2.5 mV/V/Pa.

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