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High resolution polymer coated strain sensors for in-liquid operation

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ABSTRACT

Metallic strain gauges are well studied structures for their use in force sensing. Their fabrication is rather simple, easily compatible with many techniques are broadly scalable in both quantity and resolution. Here we present a fabrication process for high resolution strain sensors (down to the nN) that can also be operated in liquid, i.e. for life sciences applications. This fabrication method offers a very high yield and opens new possibilities for bioengineering, as for example single cell studies.

1. Introduction

Polymer-based micromechanical systems (MEMS) have been increasingly used in biomedical applications [1,2]. They offer several advantages over conventional fabrication methods such as lower costs, lightness, transparency, flexibility and biocompatibility [3]. This is why, several types of MEMS like microfluidic devices [4], pressure sensors [5], implantable devices [6], tactile sensors [7] and temperature sensors [8] have already a polymer-based version. Of particular interest for cell studies are high sensitivity force sensors, which are typically addressed with the optical processing of bending structures like arrays of narrow pillars [9]. However, this high force sensitivity cannot be achieved for a large measurement bandwidth. In order to achieve larger bandwidth, it is more advantageous to move into an electrical read-out.

Microscale strain sensors are of particular interest in MEMS because of their ability to measure force, acceleration, pressure or sound and their broad applicability in robotics, space based systems, sports and therapeutics. They provide an integrated solution for electrical read-out, allowing simple data acquisition and processing in addition to the mentioned larger measurement bandwidth compared to optical techniques [10]. MEMS force sensors with electrical detection have long been proposed and demonstrated via piezoresistive detection [11,12] and metallic strain gauges [13] among others.

This latter concept has been presented in the past within polymer-based MEMS [6,14,15]. The choice of the polymer structural material is quite critical to determine the sensitivity of the final measurement. Among the most versatile materials for fabricating highly flexible strain gauges is polydimethylsiloxane (PDMS) due to its simple fabrication, biocompatibility and low Young's modulus. One method to implement strain gauges on PDMS is by directly depositing metal on top of a PDMS layer. This method has successfully been used to fabricate implantable strain sensors to assess bone morphology [6] or for neuroprosthetic applications [15]. However, the presence of thin metallic layers affects strongly the overall stiffness of the structure. When high flexibility is needed, it is more convenient to replace metal for fillers such as conductive carbon fibers [16], carbon nanotubes [17] and graphene [18]. Overall, the main drawback for PDMS based strain sensors is their permeability, that hampers their performance in determined gas environments and it makes operation in-liquid immersion impossible due to unstable electrical measurements.

Materials such as SU-8 or polyimide (PI) are better candidates for in-liquid measurement stability while still being 1–2 orders of magnitude softer than standard MEMS materials. Polyimide-based strain gauges have been fabricated by evaporating metal on PI sheets for up to 2% tensile strain measurement at temperatures as high as 200 °C [8]. Similarly, metal strain sensors on SU-8 substrates have been reported to measure the forces exerted by small organisms such as *C. elegans* on top of microfabricated pillars [10].

In this paper, we present a force sensor based on SU-8 coated strain gauges for in-liquid measurements with a large bandwidth and a very high resolution, where some of the fabricated structures, measure forces as small as 10 pN.

2. Design

The chosen approach to achieve high sensitive in-liquid force sensing is based on the use of a hybrid stiffness microelectromechanical (MEM) device composed by thin and narrow SU-8 beams with metallic gauges embedded into them [14] placed in a Wheatstone bridge configuration as can be seen in Fig. 1a. The choice of metal as a strain sensor (as opposed to semi-conducting materials or polymer-based conducting materials) is motivated to have a low electronic noise, both Johnson, 1/f and shot noise. In particular we choose gold because

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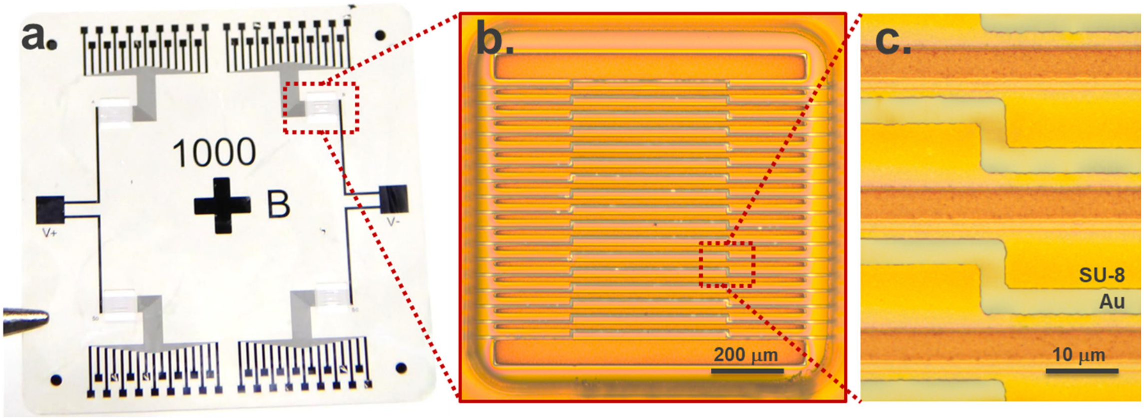

Fig. 1. Strain sensor device: a. A picture of the released device showing the four sets of strain sensors in a Wheatstone bridge configuration. b. An optical image of one of the sets of strain sensors when it was still attached to the Si wafer coated with a Cu layer. c. Zoom in of the U shape design of the strain gauges and their separation with the SU-8 coating and between gauges.

of its good resistivity and large Poison ratio, which also determines a large piezometallic coefficient. SU-8 has been selected not only because it can be patterned via optical lithography and its Young's modulus has an optimum value for the envisaged applications but also for its high dielectric strength and insulating capability even for very thin layers [19].

Initial finite element method (FEM) simulations estimate that devices that can be fabricated via standard UV lithography (lateral dimensions limited to 1 µm resolution), can yield minimum detectable values of force around ~500 $\mathrm{pN}/\sqrt{\mathrm{Hz}}$ over a large bandwidth due to the combination of metal gauges and AC bias (thus suppressing $1/f$ noise even more). Fig. 1b, taken with a 10× objective on an optical microscope, reveals gauges of 1 mm length with 3 µm width. There are three different gauge lengths: 600 µm, 850 µm and 1000 µm. These structures are meant to measure in-plane forces, therefore, to make them more sensitive the metal gauge has a U shape in the center shown with a zoom in Fig. 1c.

Within this first generation and regarding the width dimension of the gauges, we include devices with large safety margins to ensure good fabrication yield and devices for which we push the limits of our optical lithography equipment. After careful simulations using Finite Element Modelling we obtain a range for the responsivity of our devices ranging from 0.2 $\frac{\mathrm{ppm}}{\mathrm{nN}}$ ($L = 600\ \mu\mathrm{m}$, $w_{beam} = 20\ \mu\mathrm{m}$, $w_{res} = 4\ \mu\mathrm{m}$) till 0.6 $\frac{\mathrm{ppm}}{\mathrm{nN}}$ ($L = 850\ \mu\mathrm{m}$, $w_{beam} = 10\ \mu\mathrm{m}$, $w_{res} = 2\ \mu\mathrm{m}$). Considering a bias voltage of 1 V, and a noise of around 5 $\frac{\mathrm{nV}}{\sqrt{\mathrm{Hz}}}$, we can see that the estimated resolution is between 10 and 25 $\frac{\mathrm{pN}}{\sqrt{\mathrm{Hz}}}$.

3. Fabrication

The fabrication process of polymer coated strain sensors (shown in Fig. 1) is based on the multiple spin-coating, exposure and development of different thickness formulation of SU-8 resist (from Gersteltec) on a silicon wafer, being the latter used as a support.

The silicon wafer (100 mm diameter) is sputter-coated with 200 nm of copper (a 10 nm layer of Cr is also deposited to enhance adhesion) as shown in Fig. 2a. The first layer of SU-8 deposited is a thin formulation, GM1010 at 1500 rpm for a final thickness of 100 nm. The layer is soft baked (90 °C for 10 min) and exposed under UV light to pattern the

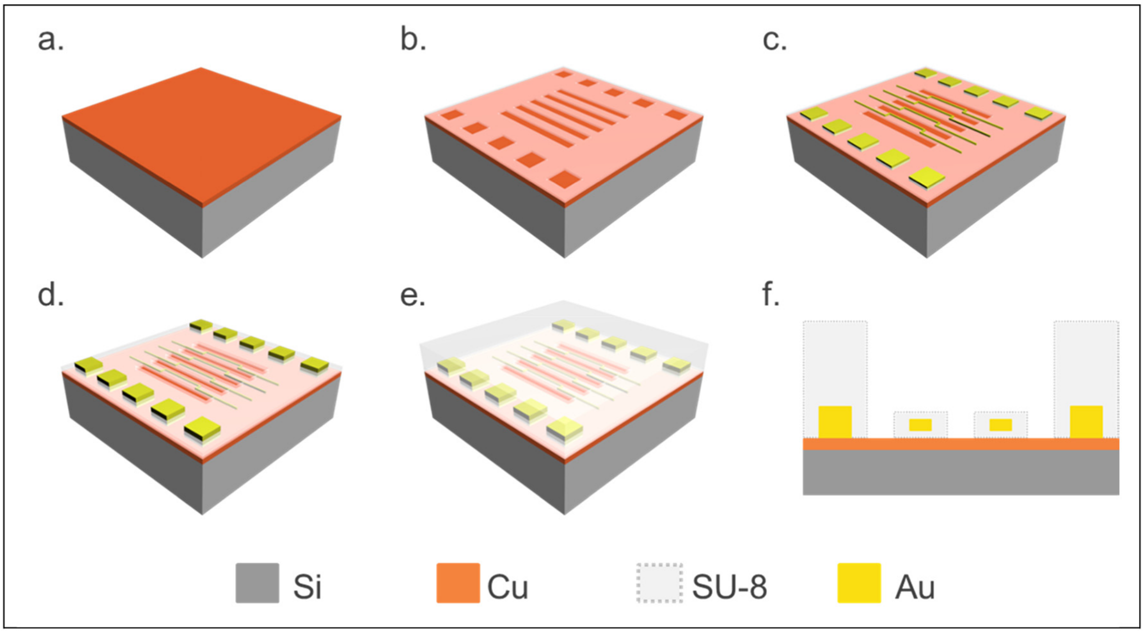

Fig. 2. Fabrication steps and device section: a. A silicon wafer is coated with Cu. b. A thin layer of SU-8 is deposited and fully processed. c. A gold evaporation is deposited through lift off process. d. A second thin layer is processed to fully coat the gold strain gauges. e. A thick layer of SU-8 is deposited and is fully processed to a final structure showed in cross section in f.