Sensors and Actuators A 228 (2015) 9–15

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Comparing membrane- and cantilever-based surface stress sensors for reproducibility

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ARTICLE INFO

*Article history:*
Received 10 September 2014
Received in revised form 13 January 2015
Accepted 18 February 2015
Available online 9 March 2015

*Keywords:*
Bio/chemical sensor
Nanomechanical sensor
Surface stress
Piezoresistive readout
Reproducibility

ABSTRACT

Point-of-care (PoC) applications require small, fast, and low power sensors with high reliability. Despite showing promising performances, nanomechanical sensors have not yet demonstrated the excellent reproducibility of measurements necessary to be incorporated in such systems. Coffee-ring effect usually occurs during the deposition of the functionalization layer and produces an inhomogeneous and poorly repeatable profile on the sensor surface. In this study, we investigated how cantilever-based sensors and the previously developed membrane-type surface stress sensor (MSS) are affected by an inhomogeneous functionalization. We functionalized 8 piezoresistive cantilevers and 16 MSS with a dextran solution that formed an inhomogeneous layer due to the coffee ring effect. During expositions to humidity pulses, MSS was five times more reproducible (standard deviations between 5% and 6%) compared to the cantilever-based sensors (standard deviations between 25% and 28%). In fact, the cantilever-based sensors were as reproducible as their functionalization layer while the reproducibility of MSS was only limited by the tolerances of their fabrication. This sensor-to-sensor reproducibility, combined with a high sensitivity, makes the MSS a promising bio/chemical sensor platform for reliable and label-free detection of substances to be integrated into PoC systems.



## 1. Introduction

Point-of-care (PoC) systems are expected to revolutionize the way doctors care for patients [1]. Instead of centralizing the patients into medical centers, care services such as diagnostics or health monitoring are brought to their home. This paradigm shift in health care promises to dramatically reduce medical costs and improve patients' quality of life [2]. Two of the most successful examples of PoC systems, which have been already used for a few decades, are the home pregnancy test and the single-use glucose sensors used by diabetics [3,4]. As highlighted by these two applications, there are four main requirements for PoC systems: portability, ease of use, cost efficiency, and reliability.

PoC systems are increasingly incorporating bio/chemical sensors based on microtechnologies owing to their small size, low power consumption, and mass production compatibility. Many sensing techniques possess outstanding capabilities to detect specific analytes at minute concentrations in real-time. Those include, for example, surface plasmon resonance sensors [5], chemoresistors [6], surface acoustic wave sensors [7], and silicon ion-sensitive field effect transistor (ISFET) with nanowires [8]. In the last decade, another technology that has attracted a lot of interest for PoC or gas sensing applications employs devices based on nanomechanical sensors [9]. These devices rely on functionalized microcantilevers, which have been initially developed for atomic force microscopy [10]. The functionalization process is often carried out by an inkjet spotter or capillaries with solutions of selected polymers or chemicals that form self-assembled monolayers [11,12]. The functionalization layer deposited on the cantilever surface reacts with surrounding molecules and yields a deflection. Depending on the nature of this layer, various analytes, such as explosives, volatile organic compounds, and antigens, can be detected [13–16]. Furthermore, with adequate readout systems, measurements can be carried out in both gaseous and liquid media.

Despite their promising performances and versatility, cantilever-based sensors commonly suffer from low sensor-to-sensor reproducibility, which limits their introduction into commercial PoC or gas sensing systems. From experience, we hypothesize that this issue is due to a poorly reproduced

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http://dx.doi.org/10.1016/j.sna.2015.02.039
0924-4247/

functionalization layer rather than disparities between the sensors dies. Indeed, solutions deposited by inkjet spotting or capillaries are commonly subject to the coffee-ring effect, which causes inhomogeneous and poorly repeatable surface coverage [17]. An inhomogeneous distribution of the functionalization layer on cantilever-based sensors will likely impact their bending profile, leading to a poor sensor-to-sensor reproducibility.

Numerous studies have been conducted to improve the control of the inkjet deposition of polymers [18,19]. For example, it was demonstrated that the coffee ring effect can be effectively decreased and even suppressed by mixing solvents of different surface tensions [20]. This technique limits however the variety of materials that can be deposited. Another approach to overcome the reproducibility issue is to use multiple cantilevers in parallel. The cantilever-based sensors are addressed in arrays to average their signals and improve the reliability of the response. With this idea in mind, Bosco et al. have developed a DVD-based readout system that can simultaneously read statistical deflections of up to 72 cantilevers [13]. More recently, Ndieyira et al. performed quantitative studies on antibiotics efficiency using the average response of 4 cantilever chips [21]. Ideally however, the sensing platform should be more robust to inhomogeneous functionalization. It would allow using fewer sensors per experiment while increasing the confidence in the obtained results.

We recently developed a membrane-type surface stress sensor (MSS) that has already shown a remarkably improved sensitivity compared to that of conventional piezoresistive cantilevers [22,23]. In this study, we investigate the sensor-to-sensor reproducibility of MSS and compare it with that of a classic piezoresistive cantilever-based sensor. The standard deviations of similarly functionalized sensors are calculated and serve as hallmarks for their reproducibility. Using both finite element (FE) analyses and humidity sensing experiments, we demonstrate that the unique shape of MSS makes its response more robust against inhomogeneous functionalization layers than that of the conventional cantilever-shaped sensor.

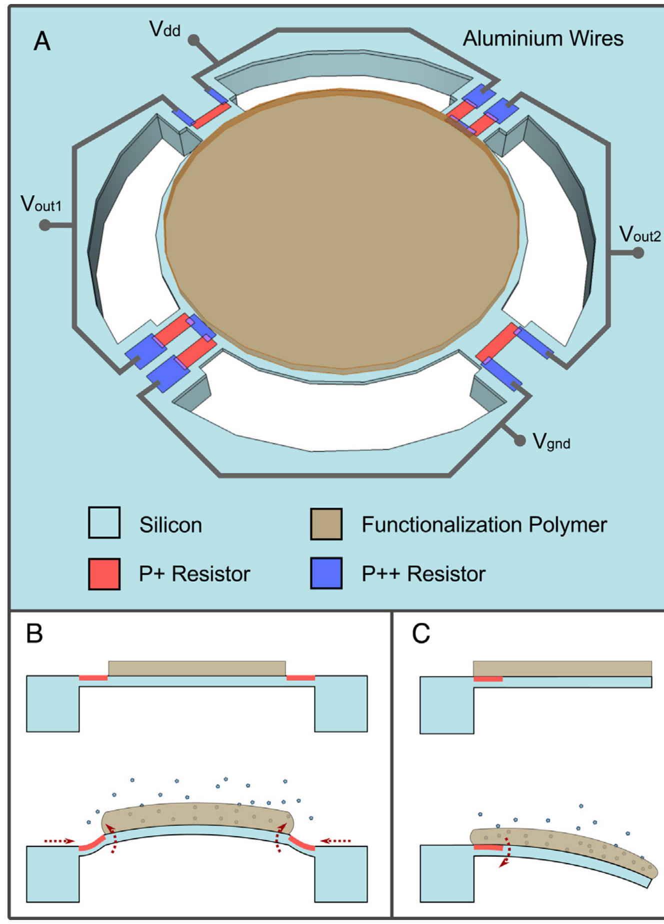


**Fig. 1.** (A) Graphical representation of a membrane suspended by four constricted beams with integrated piezoresistors connected in a full Wheatstone bridge configuration. (B) The membrane is coated with a polymer that reacts to surrounding molecules. Its swelling induces a surface stress and a deformation of the membrane that is transduced to the sensing beams. Each beam experiences compression and deflection stresses. Note that the compressive (tensile) surface stress on the upper surface of the membrane leads to the compressive (tensile) stress on the piezoresistors in contrast to a cantilever. (C) Similarly, a single clamped cantilever will bend due to the polymer swelling. However, only the deflection stress exists since the cantilever does not have any planar constraints.

## 2. Theory and modeling

### 2.1. MSS working principle

Fig. 1A shows a schematic of an MSS. A typical MSS has a round membrane with a thickness of 2.5 μm and a diameter of 500 μm. The silicon membrane is supported with four sensing beams, on which transverse and longitudinal p-type piezoresistors are integrated. Depending on a target analyte, the surface of the membrane is coated with a specific functionalization layer, e.g. a polymer. Upon absorption of volatile molecules, the polymer swells and produces a membrane deflection, which is eventually detected by the piezoresistors (Fig. 1B).

There are two major differences between the detection mechanisms of the MSS and of a cantilever-based surface stress sensor. First, unlike the latter where the cantilever simply bends (Fig. 1C), the deflection of the membrane is constrained by the four clamping beams. Hence, the surface stress applied on the membrane by the polymer layer induces two different types of stress on the clamping beams: (i) a stress due to bending of the clamping beam and (ii) a compressive stress nearly in the plane of the membrane. This additional stress component, coupled with the mechanical stress enhancement at the constricted beams and the full Wheatstone bridge configuration of the MSS piezoresistors, explains the higher sensitivity of the MSS platform compared to cantilevers [22,23]. The second difference lies in the detection configuration of the piezoresistors. In the case of a cantilever-based design, the sensing part, i.e. the piezoresistor, is integrated into the transducing part, i.e. the functionalized cantilever. The resistor detects local changes of stress induced by the functionalization layer directly above, making it sensitive to thickness variation of the latter. On the contrary, the MSS sensing parts, i.e. the constricted beams, are distinct from the transducing part, i.e. the suspended membrane. Hence, local surface stresses on the membrane are all transduced to the four beams and the piezoresistors sense a global stress. We hypothesize that, unlike cantilever-shaped sensors, the MSS are no longer sensitive to local stress variations that arise from an inhomogeneous coating. This hypothesis is tested with FE analyses and experimental comparison in the following sections.

### 2.2. Piezoresistive simulations

Piezoresistivity describes the resistance change in a material resulting from a change in local internal stress. In the case of p-type diffusion created on an n-type (1 0 0) silicon substrate, the sensitivity of a piezoresistor along the [1 1 0] crystalline orientation can be approximated by [24–26]:

$$\frac{\Delta R}{R} \cong \frac{1}{2}\pi_{44}(\sigma_{\parallel} - \sigma_{\perp}) \qquad (1)$$

where $R$ is the resistance value, $\Delta R$ is the change in resistance, and $\pi_{44}$ is one of the fundamental piezoresistive coefficients of