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How to engineer superhydrophobic micromechanical sensors preserving mass resolution

Daniele Borin[a,b,*], Mauro Melli[a,1], Simone Dal Zilio[a], Valeria Toffoli[a,b], Giacinto Scoles[c], Giuseppe Toffoli[d], Marco Lazzarino[a]

[a] CNR-IOM laboratorio TASC, Area Science Park – Basovizza, 34149 Trieste, Italy
[b] University of Trieste, Piazzale Europa, 34127 Trieste, Italy
[c] University of Udine, Dept. of Biological and Medical Science, Ospedale della Misericordia, 33100 Udine, Italy
[d] Experimental and Clinical Pharmacology Division, Department of Translational Research, IRCCS-National Cancer Institute, 33081 Aviano, Italy

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ABSTRACT

Micro- and nano-mechanical resonators such as cantilevers and pillars are more and more used as molecular sensors, due to their high sensitivity, ease of fabrication and high throughput. In order to modify their wetting properties and to prepare them for the selective adsorption of the molecules of interest, the sensor active surface has to be properly functionalized. This can significantly affect their mechanical performances. In this paper we report on the effect on a micropillar array of different hydrophobic treatments, based on plasma deposition of a fluorocarbon film (FCF) and on the formation of an alkanosilane coating, to obtain a superhydrophobic state. Each treatment was characterized by measuring the change of the quality factor in vacuum, the static contact angle and evaluating the compatibility with gold deposition, to create a bio-functional layer. As case study, DNA self assembled monolayer (SAM) formation and hybridization efficiency were measured. Finally, the superhydrophobicity was tested with diluted human plasma, as preliminary step toward the use of micropillars for biomolecular detection in human samples.

1. Introduction

Micro- and nano-electromechanical sensors (MEMS/NEMS) for molecular detection have experienced a large development in the last 10 years, with different applications in several fields [1–4]. The main advantages these sensors can offer are the extremely low limit of detection, the small amount of sample required for operation and the label-free detection of molecular species. In addition, their compact and scalable design can be combined with the fabrication technology already established for integrated circuits. As mass sensors, in highly demanding conditions (cryogenic temperature and ultra high vacuum), the ultimate resolution of a single proton was already demonstrated, using a single carbon nanotube in double clamped beam configuration [5]. These devices are gaining attention also as biomolecular sensors to be used in environmental conditions. Although in these conditions the limit of detection reduces to attogram (10^{-18} g) in air [6] and to nanogram (10^{-9} g) in liquid [7], MEMS/NEMS are good candidates for a new generation of fast, sensitive, highly parallel and cheap devices.

The most common example in such kind of sensors is represented by the cantilevers technology, firstly developed by Gerber and his group [8]. In these structures, the mechanical behavior is modified by the adsorption of molecules: in the static mode detection, the deflection of the structure is measured, while in the dynamic mode, the shift of the resonance frequency is tracked. So far, many examples have been developed for applications in molecular and biomolecular detection [3,9,10].

When used in dynamic mode, two important properties that describe the performance of the resonator are the sensitivity, defined as the variation of the resonance frequency versus the mass variation, and the mass resolution, i.e. the minimum mass variation detectable. This latter parameter is directly related to the quality factor (Q), that represents the sharpness of the frequency response at the resonance: the higher is Q, the narrower is the peak at the resonance, and the smaller is the variation of resonance frequency that can be measured. As a rule of thumb, the practical mass resolution of a mechanical resonator is directly proportional to the mass

* Corresponding author at: CNR-IOM c/o Area Science Park – Basovizza, Build. MM, SS 14 Km 163.5 I, 34149 Trieste, Italy. Tel.: +39 0403756462; fax: +39 040226767.
E-mail address: borin@iom.cnr.it (D. Borin).
[1] Present address: Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States.

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of the resonator and inversely proportional to the root square of Q [11]. Experimentally, Q can be obtained by dividing the value of the resonance frequency by the FWHM (full width at the half maximum of the resonance peak). From a physical point of view, the Q factor can be seen as the ratio of the energy stored in the resonator to the energy lost per cycle of vibration. The total energy lost can be considered as a sum of different loss sources, among those: internal losses, due to lattice defects, thermoelastic dissipations, etc. [12]; surface losses, due to adsorbed molecules on the surface; clamping losses, that arise from the coupling of the resonator to the substrate; viscous losses, due to the friction with the medium where the resonator oscillates. It is possible to assign a term for each source of dissipation, so that the total Q can be expressed as [13]:

$$\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_{\text{internal}}} + \frac{1}{Q_{\text{surface}}} + \frac{1}{Q_{\text{clamping}}} + \frac{1}{Q_{\text{viscous}}} + \cdots \quad (1)$$

At environmental pressure or at low vacuum regimes, the viscous losses are the main contribution to the quality factor reduction [12,14], while at high vacuum the other terms are predominant. In this latter condition, as the size of the resonator reduces, the surface losses become more and more important [12] and can be significantly affected by adsorbed molecules. Indeed, it was previously shown that a single layer of molecules can change the Q factor by more than 70% [15].

To apply these sensors in biological assays, their surface has to be modified in order to allow specific binding of the target molecule, or to tune the wetting properties. Such kind of modifications can affect severely the Q factor of the resonator and, consequently, its performances. A typical example is shown in the work of Ilic et al. [16], where nanocantilevers are used for the detection of few baculoviruses: a progressive deterioration of the resonance spectra is visible from the bare cantilever to the one coated with antibodies and the captured viruses. This leads to a less defined resonance frequency with the consequent loss in resolution.

Recently we have demonstrated [17,18] that we can improve by three orders of magnitude the response time of a micromechanical sensor, by fabricating an array of vertical resonators, or micropillars, on a silicon surface, where the Cassie–Baxter state can be obtained. This is a particular superhydrophobic state, characterized by extremely low interaction between water and the solid substrate [19,20]. Here the contact angle (CA) of a water drop with the substrate exceeds 150° and the solution is pinned on top surface of the structures, while a cushion of air separates the liquid from the rest of the surface. The Cassie–Baxter state arises from the combination of high roughness, which in our devices is provided by the dense array of pillars, and the hydrophobicity of their surface, which has essentially a chemical origin. In the case of the micropillars mass sensors, the Cassie–Baxter condition is very important to avoid the nonspecific adsorption on the lateral walls, which would decrease the Q factor of the sensor and would introduce spurious resonance shifts due to uncontrolled mass deposition.

To use micropillars in the Cassie–Baxter state, we need to apply a proper treatment that, at the same time: (a) makes the pillars surface hydrophobic enough; (b) maintains high values of the quality factor in vacuum, preserving the mass resolution; (c) allows the formation of a bio-functional layer, for the immobilization of the specific target molecules. In particular, we deposit gold on top of pillars, exploiting the well known sulfur–gold interaction to create a self assembled monolayer (SAM) of thiol-terminated biomolecules.

In this work, we studied the effect of different hydrophobic treatments, based on deposition of fluorocarbon films (FCF) and alkanosilane coatings, with respect to the three requirements discussed above. To better distinguish the quality factor variation induced by the surface coatings from all other environmental contributions, quality factor was always measured under vacuum conditions. We applied these approaches to monitor the formation of a DNA SAM and to quantify the hybridization efficiency. Finally we investigated the compatibility of the proposed approach with operation in human plasma, as preliminary step for the application of micropillars technology with medical samples.

2. Materials and methods

2.1. Pillars fabrication

Pillars were obtained by a deep dry etching of a patterned Si wafer. Details of the fabrication procedure are reported elsewhere [17]. Briefly, we started from a well cleaned Si (1 0 0) wafer, where a thin silicon dioxide layer (100 nm) was grown by Plasma Enhanced Chemical Vapor Deposition (PECVD). This was used as protective layer for the subsequent processes. A thin (500 nm) PMMA electronic resist was spun on the oxide and baked, and the wafer was exposed with electron beam lithography to define the pattern of the pillar matrix. Each pillar was designed to have a top area of $2 \times 3\ \mu m^2$. After development, a Ni mask (20 nm) was created by e-beam evaporation and subsequent lift-off. The sample was exposed to oxygen plasma to remove surface impurities, then to argon plasma to better define the Ni mask and remove metal residuals of the lift-off step. Vertical micropillar structure was obtained in an Induction Coupled Plasma (ICP) Deep Reactive Ion Etching (DRIE) through a BOSCH^{TM}-like process: it consists of repeated cycles of etching, using SF_6 and Ar, and passivation, using C_4F_8 and Ar. The number of cycles defines the height of the vertical structure (around 12 μm). The recipe was optimized in order to obtain a controlled undercut (approximately 2–3°), that reduces the base of the pillar and improves the oscillating behavior of the resonator. An example of the so fabricated matrix is reported in Fig. 1a, where the inset shows the tapered shape of the micropillar. On the background is also visible the frame that surrounds the whole array, used to protect it from mechanical damage and solution diffusion from the sides of the matrix, once the chip is fully immersed in liquid. The wafer was then cleaned in piranha solution (H_2SO_4:H_2O_2 7:3 at 70 °C for 15 min) to remove the Ni mask and residues of the passivation step, and BOE etching, to remove the SiO_2 protective layer. Finally, pillars were placed in an oven at 1100 °C for one hour in a nitrogen flux, to reduce the internal stresses on the fabricated resonator and remove residuals from the pillar surface.

2.2. Hydrophobization treatments

2.2.1. Fluorocarbon film coating

Fluorocarbon thin films (FCF) were deposited on a plasma assisted ICP reactor, starting from C_4F_8 and Ar gas precursors, similarly to what used in our previous work [18]: three different coatings were obtained by varying the flow rate of precursor gases, the applied bias and the time of exposure. Details of three different recipes are reported on Table 1: FCF1 and FCF2 recipes differ for the duration of plasma deposition, while in FCF3 we avoided Ar as activator agent and reduced the power applied to the coil and the process time.

2.2.2. Alkanosilane deposition

We formed an alkanosilane coating on the micropillar surface through two different processes: octadecyltrichlorosilane (OTS) evaporation in a vacuum jar for different times (1 h or 3 h) and OTS deposition from a 1 mM solution in dry toluene for 1 h. This latter treatment was performed inside a glovebox filled with anhydrous nitrogen. Before the exposure to OTS, micropillar arrays were treated with the Standard Cleaning-1 (SC-1) solution, a base-peroxide solution commonly used in microfabrication to clean the surface of Si wafer and make it more hydrophilic. Pillars not treated