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Design of Miniaturized, Self-Out-Readable Cantilever Resonator for Highly Sensitive Airborne Nanoparticle Detection †

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Abstract: In this paper, a self-out-readable, miniaturized cantilever resonator for highly sensitive airborne nanoparticle (NP) detection is presented. The cantilever, which is operated in the fundamental in-plane resonance mode, is used as a microbalance with femtogram resolution. To achieve a maximum measurement signal of the piezo resistive Wheatstone half-bridge, the geometric parameters of the sensor design were optimized by finite element modelling (FEM). Struts at the sides of the cantilever resonator act as piezo resistors and enable an electrical read-out of the phase information of the cantilever movement whereby they do not contribute to the resonators rest mass. For the optimized design, a resonator mass of 0.93 ng, a resonance frequency of ~440 kHz, and thus a theoretical sensitivity of 4.23 fg/Hz can be achieved. A μ-channel guiding a particle-laden air flow towards the cantilever is integrated into the sensor chip. Electrically charged NPs will be collected by an electrostatic field between the cantilever and a counter-electrode at the edges of the μ-channel. Such μ-channels will also be used to accomplish particle separation for size-selective NP detection. Throughout, the presented airborne NP sensor is expected to demonstrate significant improvements in the field of handheld, MEMS-based NP monitoring devices.

Keywords: nanoparticles; self-reading femtogram balance; cantilever resonator; FEM simulations; electrostatic particle collection

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1. Introduction

Particle pollution holds a great risk of adverse health effects on human organism. The size of the particle has a major dependence to this toxicity of airborne particles. Thus, "fine particles" with diameter less than 2.5 μm and "ultrafine particles (UFPs)" of diameter <100 nm can enter organism easily via the respiratory tract [1]. Especially, nanoparticles (NPs) are suspected to trigger alveolar inflammation and may lead to cardiovascular diseases [2]. Due to an increasing use of NPs in industry and consumer goods, there is a great need of a small, high sensitive and low cost detector system for real-time NP monitoring. Optical sensors cannot detect UFPs due to their vanishing scattering cross-section. Therefore, various types of resonant micro/nanoelectromechanical systems (M/NEMS) were developed as mass-sensitive airborne particle sensors to meet the demands (e.g., a nanomechanical resonant filter-fiber [3], a thermal-piezo-resistive SOI-MEMS oscillator based on a fully differential mechanically coupled resonator array [4], a piezoresistive cantilever with integrated μ-channel and μ-pillars for particle size selection [5]).

M/NEMS resonators work as a microbalance, where smallest mass changes result in a resonance frequency shift and enable a real-time particle monitoring. In previous works, we demonstrated this principle of airborne NP mass-concentration monitoring using a novel handheld device based on a silicon cantilever resonator [6]. The in-plane deflecting piezo-resistive cantilever was connected to a phase-locked loop (PLL) circuit to realize the real-time frequency tracking [7]. Nevertheless, for the detection of low concentrations of UFPs, the resonator size and mass had to be miniaturized. Therefore, we demonstrated femtogram mass detection of single airborne NPs of 100 nm in diameter using vertical silicon nanowire resonators [8]. However, so far the resonance frequency analysis of the nanowires has not been performed in ambient air, but inside a scanning electron microscope (SEM), which is not practicable for a real application. Furthermore, particle size separation has not been investigated yet. Therefore, the integration of μ-channels with multiple sensors in an array is considered here.

2. Sensor Concept and Design Optimization

For highly sensitive NP detection, a small resonator rest mass is needed. Therefore, we designed a one-side-clamped cantilever with external, piezo resistive struts for an out-reading Wheatstone half-bridge as shown in Figure 1a. We obtain a very small resonator mass corresponding to a low, fundamental in-plane resonance frequency of $f_0 \approx 440$ kHz. To optimize the design parameters, several finite-element modelling (FEM) simulations using COMSOL Multiphysics 4.4b were performed. Therefore, to keep f_0 constant under the assumption of $f_0 \sim w_C/l_C^2$ for a homogeneous rectangular cantilever we tuned the cantilever length l_C by a factor of $\sqrt{(1 + \Delta w_C/w_C)}$, while an initial cantilever width $w_C = 2$ μm was increased by Δw_C. Also, we kept the strut width w_S equal to w_C.

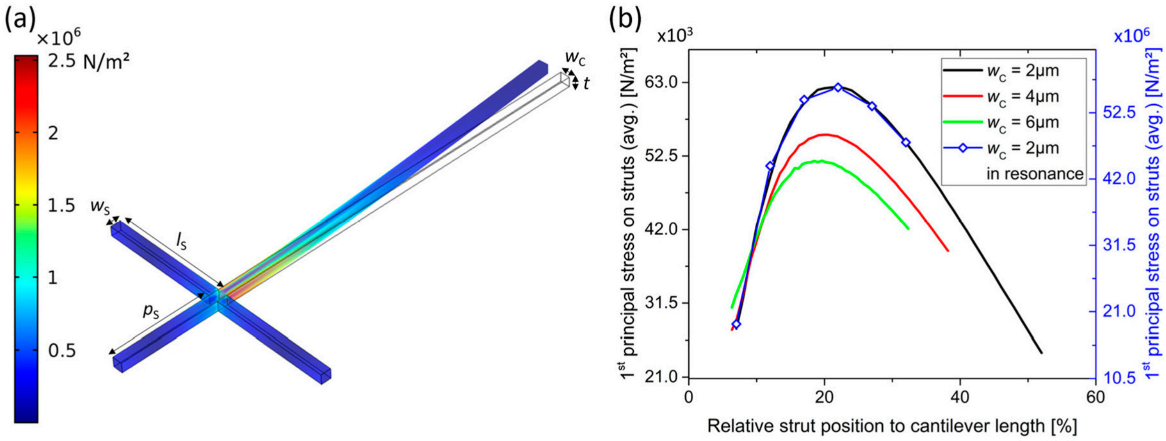

Figure 1. (**a**) Cantilever deflection by FEM upon in-plane excitation with the generated von Mises stress marked by colouring and (**b**) first principle stress on average over a piezo resistive strut vs. strut position along the cantilever length.

Figure 1b shows a comparison of the first principal stress on average over a piezo resistive strut for different strut positions p_S along the cantilever length using dynamic base excitation in resonance and a stationary body load of 1.4 μN applied to the sensor for a width and length of 2 μm and 100 μm, respectively. Both methods show similar behaviour. Due to its simplicity, we then used the stationary body load to find the optimum p_S relative to l_C and compared the results for $w_C = 2$ μm, $w_C = 4$ μm and $w_C = 6$ μm. We found a maximum stress for $p_S \approx 0.2\ l_C$ from the clamped end. Correspondingly, we found optimum widths w_S and w_C and structure thickness t at their minima (2 μm) with a minor dependency on w_S and w_C. To avoid non-linearity and movement of the struts, we chose a strut length l_S of 25 μm, although the first principal stress for varied l_S shows a flat maximum between 30 μm and 40 μm.

The design parameters chosen for fabrication are listed in Table 1. The sensors are being fabricated using silicon-on-insulator (SOI) wafers and micromachining techniques, which mainly employ photolithography, thermal oxidation, doping boron and phosphorus diffusions, metal evaporation and inductively coupled plasma (ICP) cryogenic dry etching processes. We assume a *p*-diffusion depth of ~1.4 µm (measured by a monitor sample using an electrochemical capacitance-voltage (ECV) profiler), which defines the piezo resistive, stress-sensitive part of the struts.

Table 1. Optimized cantilever dimensions and strut position.

Parameter	Value (µm)
Strut/cantilever width w_S and w_C	2–4
Cantilever length l_C	$100 \times \sqrt{(w_C/2)}$
Strut length l_S	25
Strut/cantilever thickness t	2
Strut position p_S (from clamped end)	0.2 l_C

3. Particle Collection

For particle collection, we are using an electrostatic field between an electrode on the cantilever and an integrated counter electrode on the edges of the µ-channel. We already used this principle in previous works and were able to efficiently collect particles by their natural charge [6,7]. Figure 2 shows the cantilever sensor and collection device. In this case, the distance of cantilever and counter electrode is ~3 mm, and a collecting voltage of 300–600 V is needed for particle collection. Figure 2 also depicts electrostatic collected carbon NPs on the cantilever resonator.

Due to the strongly reduced distances of <25 µm and the µ-channels that focus the particle stream, we expect an increased collection efficiency for our new sensor design. The sensor sensitivity can be estimated by $f_0/\Delta f \approx 2m_0/\Delta m$, where Δm is the particle mass, Δf is the corresponding frequency shift, m_0 and f_0 are the resonators mass and eigenfrequency, respectively [7]. With a reasonable frequency resolution Δf of 1 Hz, a mass detection sensitivity of ~4.3 fg can be expected, which corresponds to a single spherical carbon particle (density of 2.6 g/cm^3) with a diameter of 150 nm.

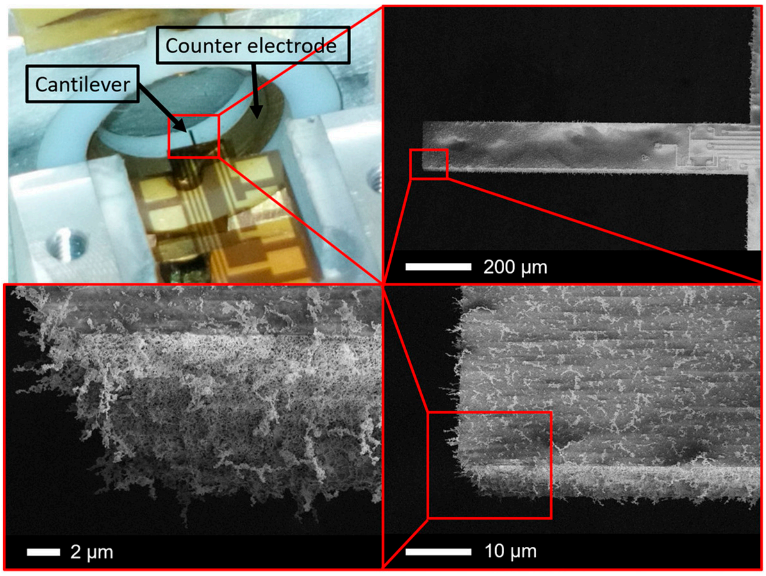

Figure 2. SEM images of a cantilever resonator with electrostatically collected NPs.

4. Conclusions

The design optimization using finite element modelling (FEM) and sensor concept of a self-reading miniaturized cantilever for highly sensitive airborne NPs detection have been presented. For a minimum resonator mass of 0.93 ng and a theoretical sensitivity of 4.23 fg/Hz while using standard photolithography-based fabrication processes, external struts, are used as strain gauge resistors connected in a piezo-resistive Wheatstone half bridge. A μ-channel to focus the particle stream and electrodes for electrostatic particle collection were integrated. Sensor samples are currently in fabrication using silicon-on-insulator (SOI) wafers and will be tested with respect to reference measurement systems using engineered NPs. Furthermore, μ-channels and sensor arrays will enable size separation for selective particle detection and increased measurement accuracy by an enlarged collection area and statistical analysis.

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Conflicts of Interest: The authors declare no conflict of interest.

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