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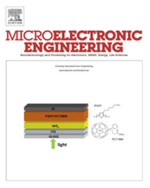

Solid-gap wine-glass mode disks VB-FET resonators applied to biomass sensing

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ABSTRACT

The working principle of an electromechanical resonator for mass sensing applications is based on monitoring the characteristic resonance frequency downshift due to the particles attachment on the surface of the device. Solid-Gap Vibrating-Body Field Effect Transistor (VB-FET) resonators offer an interesting solution for extreme biomass sensing due to their high motional current at resonance, their compatibility with Complementary Metal-Oxide-Semiconductor (CMOS) circuits, high reproducibility of characteristics and the possibility to have exploitable values of the quality factor (*Q*-factor) in air and liquid operation. In this work a detailed micromechanical analysis of VB-FET disk resonators is carried out, considering geometrical design parameters, geometrical variability, motional resistance for air and solid-gaps, *Q*-factor and variable particle-resonator sensing cases, permitting quantitative discussions on their suitability for biosensing.

1. Introduction

The actual tendency of decreasing the size of the mechanical resonators into submicron domain is very promising for the development of ultrasensitive chemical and biological mass sensors able to reach extremely low mass resolutions. The working principle of such sensors is based on monitoring the characteristic resonance frequency downshift due to the particles attachment on the surface of the resonator.

Recently, resonant mechanical nano-balances have been proven to achieve an experimental point mass sensitivity of 1.6 kHz pg^{-1} for individual submicron airborne particles [1]. In the same way, airborne nanoparticles have been detected by vertically aligned silicon nanowire (SiNW)-based resonators revealing a point mass sensitivity of 7.1 Hz fg^{-1} [2]. For applications where the mass is deposited as a uniform layer on the surface of the resonator the Figure of Merit (FOM) to be considered is the distributed mass sensitivity that measures the minimum mass that can be detected per square meter of sensing surface [3]. Mass sensors based on Quartz Crystal Microbalances (QCM) have yielded a distributed mass resolution of 700 pg cm^{-2} and those based on Thin-Film Acoustic Wave Resonators (TFBAR) technologies have accomplished a distributed mass resolution of 1000 pg cm^{-2} [4], nevertheless they cannot be easily integrated into silicon process. Silicon resonant cantilever and mass sensors based on Carbon Nano-Tubes (CNT) have achieved subatomic distributed mass resolution, however the needed readouts have not been miniaturized and their manufacturing reproducibility has been proven to be low.

In order to integrate the actuation and the readout, square bulk mode resonators with electrostatic transduction and a distributed mass sensitivity of 125 pg cm^{-2} [5] as well as disk bulk mode resonators achieving 8.7 pg cm^{-2} [3] have been implemented, nonetheless, due to their reduced transduction area a small motional current is extracted from the devices and is interfered by the frequency floor noise, revealing the importance of better amplification in the mass sensors readout. The high motional resistance R_x, due to the relative inefficiency of the air–gap in electrostatic transduction has boosted the fabrication of 2 μm-solid-gap Radial Contour Mode (RCM) resonators for the detection of goat immunoglobulin G (IgG) achieving a mass sensitivity of 1617 Hz nm^{-2} and a motional resistance of 6.5 MΩ [4], which is still too high to be compatible with Integrated Circuits (IC).

Solid-gap VB-FET resonators are vibrating structures embedded into FET transistors fabricated in Silicon-On-Insulator (SOI) that integrate both actuation and readout on-chip and perform a remarkable amplification in the readout [6] as well as R_x reduction due to the high-*k* dielectric into the gap. In this work we present the preliminary micromechanical analysis to fabricate a VB-FET

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disk resonator, taking into account materials, geometrical design parameters, motional resistance, *Q*-factor and point and distributed mass sensitivities.

2. Principles of operation

The device consists in a silicon disk suspended by two anchors corresponding to the drain and the source electrodes of the VB-FET (see Fig. 1). The structure is enclosed by two polysilicon capacitive gate electrodes that are fixed and spaced from the perimeter of the movable transistor body by high-*k* dielectric solid-gaps. The body of the resonator is p-type doped and the drain and source regions are highly n-type doped what results in the creation of two modulated channels in the areas of the disk that are controlled by the gates.

The VB-FET is electrostatically driven in resonance with a two-port AC-DC actuation: a bias voltage V_p, is applied to the disk by means of the drain electrode, and two AC-DC voltages, V_{G1} and V_{G2}, are applied to the gates. When the frequency of the AC electrical signals matches the Wine-Glass Mode (WGM) resonance frequency of the disk, the resulting mechanical force drives the disk into a characteristic vibration mode shape in which the disk expands and contracts modulating the gaps. The mechanical modulation of the gaps results in an electrical modulation of drain-to-source current I_D existing in the channels that face the gaps. I_D is collected in the source electrode and contains the contributions of the capacitive, piezoresistive and field-effect currents as it has been already proven in [6,7].

3. Design

The present work is focused on the micromechanical Finite Elements Methods (FEM) analysis of disk resonators to study the benefits of the solid-gap regarding to resonance frequency, R_x, *Q*-factor and point and distributed mass sensitivity. Fig. 3 shows the perspective-view schematic for the resonator: a solid disk with radius *R*, thickness *t*, anchor length l_{anchor}, anchor width w_{anchor} and solid-gap *d*. The two anchors correspond with the drain (connected to V_p) and source (connected to ground), as it has been reported in Figs. 1 and 2. The gates surround the solid-gaps, (in blue) and excite the disk by means of a harmonic perturbation as it is mentioned in Section 2.

Aside from the variants that are specified later, the typical dimensions considered in this work are: $R = 5\ \mu\text{m}$, $t = 1\ \mu\text{m}$, $d = 50\ \text{nm}$, $l_{\text{anchor}} = 1\ \mu\text{m}$ and $w_{\text{anchor}} = 750\ \text{nm}$, and four anchors have been simulated.

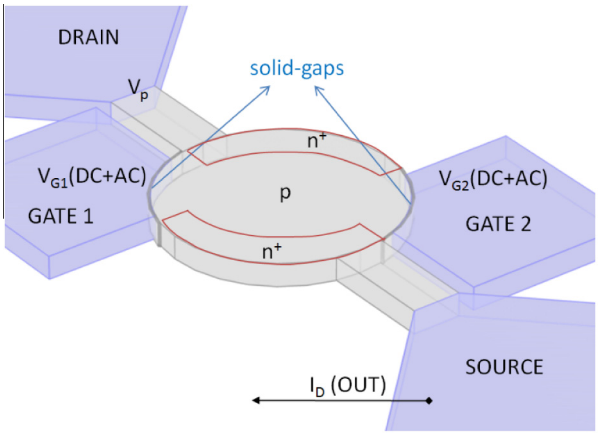

Fig. 1. Perspective-view schematic of the wine-glass mode disk resonator in a typical two-port bias and excitation configuration. The solid-gaps face the inversion channel regimes.

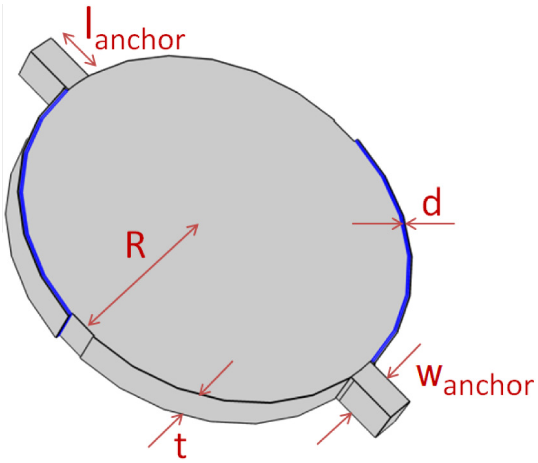

Fig. 2. Perspective-view schematic of the simulated micromechanical wine-glass mode disk resonator.

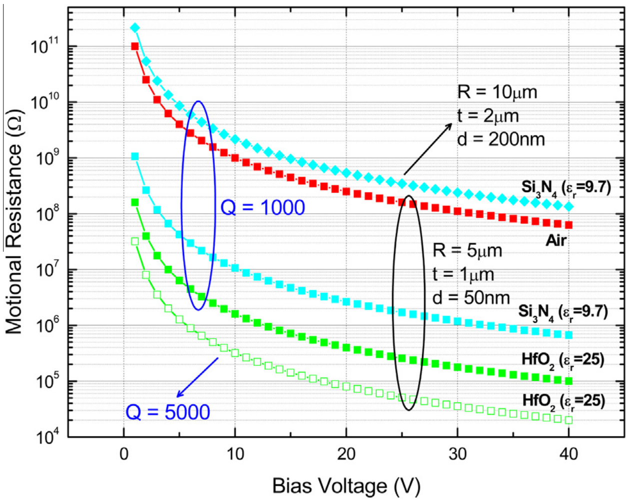

Fig. 3. Motional resistance, R_x, in function of the bias voltage, V_p, from analytical simulations for bulk disks by considering different parameters.

4. Results

4.1. Motional resistance

The equivalent LCR circuit for the wine-glass disk is governed by the total integrated kinetic energy in the resonator, its mode shape and the parameters associated with its transducer ports [8]. Using the procedure of [8–10] the motional resistance for a vibrating disk can be approximated as in Eq. (1).

$$R_x = \frac{\omega_0 m_{\text{re}}}{Q\eta_e^2} \qquad (1)$$

where ω_0 is the angular resonance frequency, m_{re} is the equivalent mass of the disk vibrating at the fundamental wine-glass mode of resonance, *Q* is the quality factor of the disk and η_e is the electromechanical coupling factor in the high-*k* solid-gaps.

The electromechanical transduction is modeled by the integrated change in the electrode-disk capacitance per unit of displacement as it is included in Eq. (2), where *C* denotes the capacitance between the disk and each electrode. A is the coupling