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Mechanically Coupled Bulk-mode Dual Resonator Mass Sensor

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Abstract

The adaptation of micro- and nanomechanical resonators as mass balances for biochemical sensing has received much attention in recent years due to the potential for very high resolution and electrical readout of target analyte in a label-free format. However, several implementation challenges arise from the necessity of operation in compatible biological buffer solutions. These challenges include minimizing undesired effects of fluid-structure interaction and buffer interference with signal transduction. Electrical readout of the sensor response is complicated by coupling to the electrical properties of the buffer solution and voltage limitations due to the possibility of undesired electrochemical reactions on the sensor surface. To address this problem we propose a novel dual resonator platform, wherein electrical transduction and sensing are spatially separated onto two different mechanically coupled resonators. In this work, we demonstrate the functionality of the dual resonator system as a mass sensing platform, with a mass responsivity of 37 Hz/ng.

Keywords: Coupled resonator; mass sensor; bulk mode

1. Introduction

Over the past decades, micro- and nanomechanical resonators have advanced significantly as highly sensitive mass sensors and thickness film monitors [1, 2]. These sensors operate by transducing added mass on the resonator as a downward shift in resonant frequency. In biochemical sensing, the commercially available quartz crystal microbalance (QCM) operates using the same principle wherein the attachment of target analyte on the QCM is monitored from the frequency shift as a result of the added mass. Nano- and micro-mechanical resonant mass sensors for use in biochemical sensing have received much attention recently due to potential for very high mass resolution and electrical readout of target analyte in a label-free format, as well as the potential for integration with CMOS and microfluidic handling for lab-on-a-chip integration. However, challenges arise when implementing the electrical interface of the resonator in aqueous environment, as electrolysis of the liquid media limits voltage headroom and increased energy dissipation from fluid damping results in higher motional resistance. Additionally, coupling of the readout to the electrical properties of the buffer solution is undesirable.

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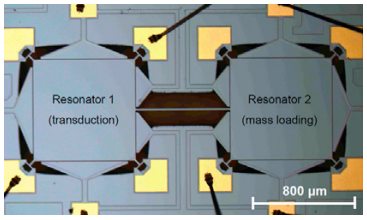
Previous approaches to address these challenges include piezoelectric/electro-thermal methods for transducing the resonant device [2-4], as well as insulating the device surface with polymer [2]. However, these methods complicate the fabrication process, and also add complexity to the material stack on the sensor surface which needs to be optimized for chemical functionalization and biocompatible operation. Electro-thermal actuation may result in undesired heating, and thermal stresses in a composite material stack may degrade the fidelity of the resonator output. In this work, we propose a novel dual resonator sensing platform to address these challenges, using two electrically transduced bulk mode silicon resonators that are mechanically coupled together via a thin beam, allowing the two to vibrate together at the same frequency. This enables the physical separation of the electrical transduction and sensing regions of the device, and hence allows for the possibility of optimizing the biosensing and physical transduction independently to a much greater extent. This paper also experimentally demonstrates the functionality of the proposed dual resonator sensing platform as a mass sensor.

2. Resonator structure and operation

The coupled device consists of two square plates which are anchored at each of the four corners via a T-shaped connecting stem. This allows the vibration of the squares in the square-extensional (SE) mode, wherein the squares extends and contracts symmetrically on all four sides. The two SE mode resonators are mechanically coupled via a coupling beam at the centre edges of the square, allowing the two resonators to vibrate simultaneously. This enables electrical transduction of the combined vibratory response to be spatially separated from the sensing zone, where one resonator is used for driving the device into vibration and sensing the combined vibratory response (transduction resonator), and the surface of the other resonator (mass loading resonator) is configured for mass sensing, as illustrated in Fig. 1a.

Two close-spaced resonances of interest exist for this structure: the in-phase SE mode, where the squares are extending and contracting symmetrically and vibrating in-phase; and the out-of-phase SE mode, where the squares are vibrating 180 degrees out of phase. The coupling beam length is designed to separate the modal peaks sufficiently apart to facilitate the precise selection of one mode for measurement at a given time [5]. Figure 1b shows an ANSYS FE simulation of the coupled device vibrating in the in-phase SE mode. The device parameters are summarized in Table 1.

(a)



(b)

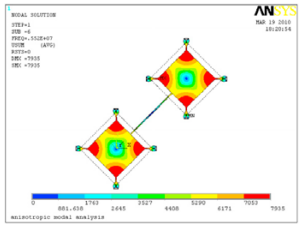


Fig. 1. (a) Optical micrograph of the coupled two resonator system, with resonator 1 being the transduction resonator and resonator 2 being the mass loading resonator; (b) ANSYS FE simulation of the coupled square resonator vibrating in the in-phase SE mode.

Table 1. Coupled device parameters

Parameters	Value
Side length of the square	800 µm
Device thickness	25 µm
Transduction gap	2.5 µm
Resonant frequency (in-phase mode, out-of-phase mode)	5.492 MHz, 5.423 MHz
Measured quality factor in air (in-phase mode, out-of-phase mode)	5139, 8508
Measured quality factor in vacuum (in-phase mode, out-of-phase mode)	7960, 33376

3. Mass sensor demonstration

To demonstrate the applicability of the coupled resonator platform for mass sensing, successive layers of chrome (Cr) were deposited over the front side of the mass loading resonator in 5 nm increments using thermal evaporation via a shadow mask. The frequency response was measured on the transduction resonator after each incremental deposition in both air and vacuum using capacitive actuation and piezoresistive sensing [6]. The schematic of the measurement setup is shown in Fig. 2a, where V_{ac} and V_{dc} is applied to the electrodes, which generates a time varying electrostatic force that drives both resonators into motion. A DC voltage V_d is applied across the two corners of the square for the detection of the vibratory response as the electrical resistance of the square changes due to piezoresistive effect. A corresponding shift in resonant frequency can be clearly observed after each deposition increments for both modes, as shown in Fig 3 (out-phase mode) and Fig 4 (in-phase mode). The sensor has a mass responsivity of 34 Hz/ng (219 Hz cm^2/μg) in air and 32 Hz/ng (209 Hz cm^2/μg) in vacuum for the in-phase mode; 36.7 Hz/ng (235 Hz cm^2/μg) in air and 37.3 Hz/ng (238 Hz cm^2/μg) in vacuum for the out-phase mode.

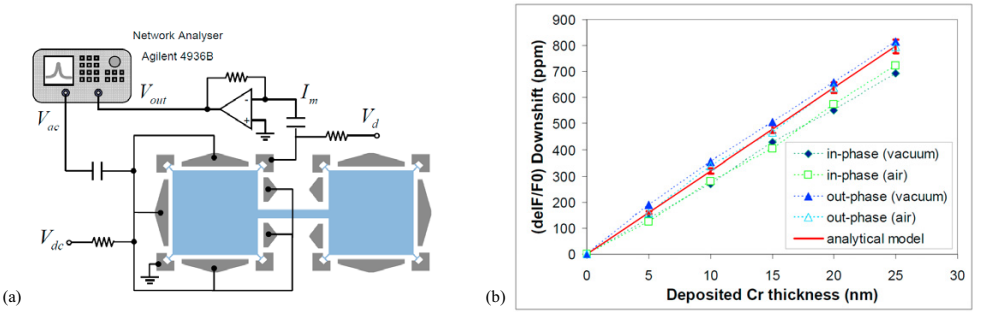


Fig. 2. (a) Schematic showing capacitive actuation and piezoresistive sensing measurement circuit for the dual resonator sensing platform. (b) Comparison between the measured resonant frequency shift and the analytical model to thickness of Cr film deposited

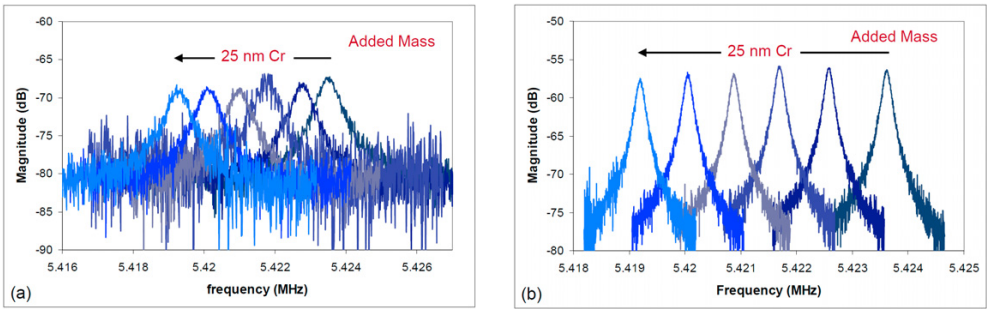


Fig. 3. Frequency response of the out-of-phase mode measured (a) in air and (b) in vacuum each time 5 nm Cr has been deposited, showing corresponding resonant frequency shift with mass loading.

The variation in frequency due to added mass is given by the relation

$$\Delta f = -(\Delta m / 2m) f_0 \quad (1)$$

where f_0, m is the nominal frequency and effective mass of the resonator. In practice, both the structures effective mass and effective stiffness will be affected when the target to be detected attaches to the resonant structure. Fig. 2b shows that the measured down shift in frequency vs. thickness of deposited Cr to be linear and the results are in close agreement with analytical modeling due to pure mass loading as predicted by equation 1.

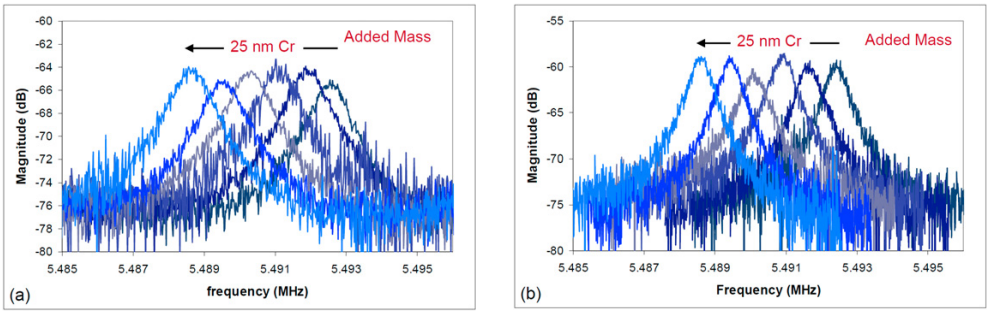


Fig. 4. Frequency response of the in-phase mode measured (a) in air and (b) in vacuum each time 5nm Cr has been deposited, showing corresponding resonant frequency shift with mass loading.

4. Conclusions

We have proposed a novel dual resonator sensing platform, wherein electrical transduction and sensing are spatially separated onto two different mechanically coupled resonators. This sensing platform addresses the implementation challenges of a biochemical sensor, where the operation in compatible biological buffer solutions is desirable. The functionality of the dual resonator system as a mass sensing platform was demonstrated via successive Cr thin film deposition, with a mass responsivity of 37 Hz/ng. The downshifts in resonant frequency due to added mass are in close agreement with analytical modeling.

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