Multi-modal analysis of out-of-plane vibration modes of thin-film circular resonators for mass sensing applications

A. Gualdino, V. Chu, J. P. Conde

INESC Microsistemas e Nanotecnologias and IN-Institute of Nanoscience and Nanotechnology, Lisbon, Portugal
Department of Bioengineering, Instituto Superior Técnico, Lisbon, Portugal

Abstract

Microelectromechanical (MEMS) structures consisting of surface micromachined, stepped-anchor disk resonators made from phosphorous-doped hydrogenated amorphous silicon (n-a-Si:H) were fabricated and their out-of-plane vibrations characterized. The dynamics of the different mode orders identified can be modeled by an effective mass associated with the vibration mode shape. Site specific binding of a target mass is proposed as a sensing principle that is calibrated by the use of multi-mode analysis. The degenerate mode frequency split that results from minor microfabrication asymmetries is also evaluated as a detection principle in resonant mass sensor applications with the purpose of developing a self-compensating system.

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Keywords: resonator; flexural; non-degenerate modes; mass sensor.

1. Introduction

Resonant microbalances typically use the well-established principle that resonant frequency shifts are related to added mass from analyte immobilized on the surface of the resonating structure [1]. However, it is essential to have a very stable system and to calibrate the measurements to account for frequency drifts that result from environmental changes. Changes in relative humidity, vacuum state, actuation voltage, presence of adsorbates, temperature and time can result in frequency variations that are not related to the mass of the target molecules added.
In this work, an experimental analysis was made to understand the effects of the operating conditions on the frequency stability. The use of non-degenerate modes is evaluated with the purpose of achieving an intrinsically calibrated measurement. Compared to the common direct frequency shift measurement, the design principle proposed has the advantage of being a self-compensated system since temperature and stress effects from probe immobilization affect both modes equally, while the frequency split remains constant. Cross referencing data from the frequency shifts in multiple modes is another route studied in this work.

The microresonators presented are based on n-a-Si:H thin-films deposited by radio-frequency plasma-enhanced chemical vapor deposition, RF-PECVD [2]. The optoelectronical and mechanical properties of n-a-Si:H thin-films suitable for devices are obtained at low processing temperatures (<250ºC) [2]. The low temperature PECVD processes used allow the fabrication of devices on a variety of substrates, in large areas and potentially in the backend process of CMOS devices.

2. Background

The generic solution of an edge-clamped plate vibrating out-of-plane has an allowed set of frequencies $\omega_{mn}$, where $m$ corresponds to the number of nodal diameters and $n$ to the number of nodal circles [3]. To each eigenvalue that represents a unique mode can be associated an effective mass that corresponds to the mass of the resonator excluding the nodal regions of displacement. The two dimensional nature of the solutions to the equation of motion results in spatially orthogonal pairs of resonant modes which are degenerate in frequency. For each frequency $\omega_{mn}$, the mode shape solution is two-fold degenerate in its angular solution (except when $m \neq 0$). Figure 1 shows the simulated deflection profiles of the degenerated modes (1,1) and (2,1) for circular disk resonator clamped at four points. The degree of the frequency splitting is not only influenced by experimental asymmetries but also the mode order and the position, number and angular separation of the anchoring stems.

Fig. 1. Simulated deflection profiles of degenerate modes (1,1) (a) and (2,1) (b) in out-of-plane disk resonators.

3. Device fabrication and characterization

The resonators in this work are fabricated using surface micromachining techniques. The structural layer is made of n-a-Si:H which is wet released from a sacrificial layer of Al (see Figure 2 (a)). The microresonator structures are actuated electrostatically. Resonance vibrations are measured in a vacuum chamber with an optical laser deflection method described elsewhere [4]. For the mass sensing measurements polystyrene microspheres with an individual mass of ~0.55 pg were spotted on top of the resonator. The resonance frequency is determined from the peak maximum, $f_{res} = \omega_{res} / 2\pi$ and the quality factor $Q$ of the resonances is evaluated by the 3dB attenuation bandwidth, $Q = f_{res} / \Delta f_{-3dB}$. .
Figure 2 (b) shows the frequency response of a 100 µm radius resonator with the \((m,n)\) modes identified with the help of finite element modelling results.

![Figure 2](image)

Fig. 2. (a) SEM micrograph of released disk plate resonator (diameter, \(D = 50 \mu m\); thickness, \(h = 3 \mu m\); gap to substrate, \(g = 1 \mu m\)). (b) Resonance peaks of a 100 µm radius disk resonator measured in vacuum with in-phase actuation and anti-phase actuation.

4. Experimental results

4.1 Non-degenerate modes

Because of microfabrication asymmetries the mode frequency degeneracy of the axis symmetric modes \((m \neq 0)\) is broken. The two-fold nature of the orthogonal solutions for out-of-plane vibrations in membrane resonators is experimentally observed (see figure 3 (a) and (b)). The circular disk represented shows a split of about 10 kHz for the mode \((1,1)\) and a frequency split of 574 kHz for the mode \((2,1)\). The presence of anchor points in between the nodal lines results in an increase of stiffness of the resonator that is reflected in a higher frequency shift in mode \((2,1)\) when compared to mode \((1,1)\). The frequency drifts observed for an individual mode and the difference between the frequencies of non-degenerated modes is compared. The temperature frequency drifts measured are about 100 ppm/ºC. The frequency split for the mode \((1,1)\) is not maintained and seem to increase as the temperature is increased.

![Figure 3](image)

Fig. 3. Experimental observation of frequency splitting in non-degenerated vibrational modes \((1,1)\) (a) and \((2,1)\) (b). Relative frequency variation as a function of temperature (c).
4.2 Multi-modal analysis

The impact of the presence of an additional mass located at the center of the resonating disk on the resonance frequencies of the four different vibrational modes was analysed. Figure 4 shows the resonance frequency curves before (black) and after mass immobilization (green). Because of the analyte mass distribution on top of the resonator and the mode shape the frequency variation is different from mode to mode. In the fundamental mode the frequency shift is in agreement with the frequency variation on the assumption that the spring constant is unchanged, $\delta f = -\delta m \cdot f_0 / 2m_0$, and that the mass is uniformly distributed. Since the 25 microspheres are located at the center of the disk, where the nodal lines of mode (1,1) are present the frequency shift is much smaller than in the previous case. For mode (0,2) the frequency shift is enhanced since the beads are located in the moving area of this particular mode and the effective mass is smaller.

Fig. 4. Frequency shifts due before (black) and after (green) the presence of 25 microspheres located at the center of the disk resonator. The calculated frequency shift assuming a homogeneous distributed mass load is also represented (red).

Acknowledgements

The authors acknowledge Fundação para a Ciência e a Tecnologia (FCT) for funding through the Associated Laboratory–Instituto de Nanociência e Nanotecnologia IN and project PTDC/CTMNAN/122226/2010. A. Gualdino acknowledges FCT for a PhD grant (SFRH/BD/48158/2008).

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