Development and Characterization of High Frequency Bulk Mode Resonators

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Abstract:
In the past, numerous publications [1,2] suggested the use of static and dynamic cantilevers to detect the biochemical molecules like proteins and DNA strings.
This article describes the development of a bulk mode resonator which can be employed for detection of bio/chemical species in liquids. The goal is to understand the mechanical and electrical properties of a bulk mode resonator device which exhibit high frequency resonance modes and Q-factor. A high resonance frequency is desirable because a small change in the resonator's mass, for example because biological molecules bind to the surface of the resonator, gives a large change in resonance frequency.
With bulk mode resonators, the resonance frequency can be dramatically increased compared to cantilevers. This improves the efficiency of the resonator allowing it to detect very small mass changes as is necessary to detect biological samples. We believe that this type of resonators can be used for realizing highly sensitive biosensors.

Keywords: High resonance frequency, high Q-factor, bulk mode resonator, disk, capacitance detection/ read-out and biosensors.

1. Introduction

Designing a nano or micro-electromechanical system (NEMS and MEMS) cover many physical domains such as the mechanical, electrical, thermal and optical. All these domains interact with each other adding to the difficulty of analyzing them individually.

The purpose of a bulk mode resonator presented in this work is to measure biological samples for example DNA or proteins [3]. A bulk mode resonator can be used to measuring the mass of specific species present in an aqueous solution [4]. This kind of device is based on a high frequency mechanical resonator. When looking at mass sensors for use in liquids the most important parameters are:

1) High resonance frequency
2) Low damping losses expressed by a high Q-factor

To optimize for these parameters, we simulated a electromechanical model of different designs with varying radii in order to predict the maximum current level at resonance and the amplitude of the frequency response. The disk and ellipse resonators were simulated for different classes of designs, such as designs with one anchor point, two anchor points and a stem at the centre of the disk.

In a mechanical device like a bulk resonator, shrinking the radius will increase the resonance frequency. However, this complicates the fabrication as it requires more advanced and time-consuming processing steps. Therefore, simulations are an important key to optimizing the design of these resonators before commencing fabrication.

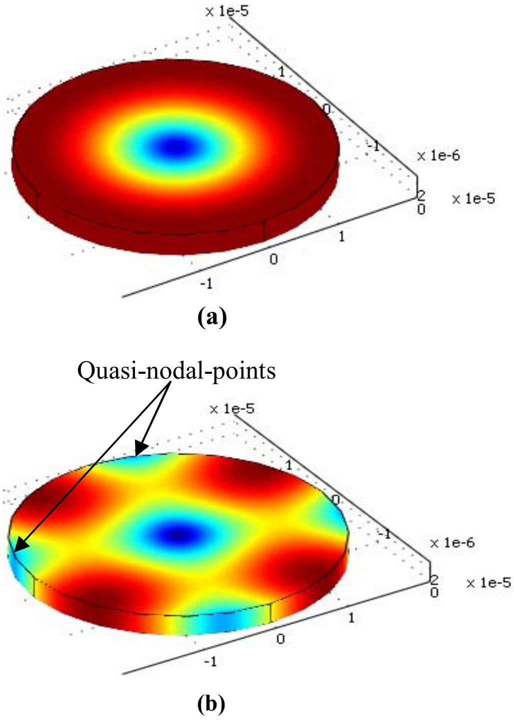
The results of the simulation are used for designing and fabricating a resonator with better electrostatic and mechanical behavior and higher resonance frequencies for many kinds of geometries, e.g., disk and ellipse bulk resonators.

2. Theory

Two different resonance modes those are preferable for bulk resonators. The two modes are called *breathing mode* and *wine-glass mode*, respectively. Figure 1 illustrates the symmetries of the two resonance modes.

The *breathing mode* (figure 1(a)) gives higher resonance frequency than the *wine-glass mode*. This is caused by the breathing mode having a much higher effective stiffness compared to the *wine-glass mode*. [4]

The wine-glass vibrational mode depends on the expansion and contraction of the disk. This mode gives four quasi nodal points on the disk (figure 1(b)). In this mode, the disk expands along one axis and contracts in the perpendicular direction. [5,6]



(a)

(b)

Figure 1: (a) The *breathing mode* for a circular resonator simulated in COMSOL. (b) *Wine-Glass mode* with 4 quasi nodal points simulated in COMSOL.

3. Experimental Work

This section describes the fabrication of bulk mode resonators. To ease the fabrication of resonators with different geometry, all designs are based on a template chip. The individual resonators are milled out using the Focused Ion Beam (FIB) microfabrication method.

The idea is to make bulk mode resonators in different shapes by using FIB. Before the chips are fabricated using FIB, the chip layout is designed using L-edit, a CAD-program for designing and developing masks for microfabrication processes.

Resonators produced using this process only allows the wine-glass mode due to the need of lateral clamping. The micro resonator device is illustrated in figure 2, with a close-up on the disk in figure 3. The green layer is a disk microresonator in poly-silicon, the orange layers are the electrodes also fabricated in poly-silicon. The gray areas are aluminum metal contacts for better electrical contact to the electrodes. There is an air gap between the disk and the electrodes. The gap is approximately 100 nm wide. The blue layer is silicon dioxide (SiO_2) and the electrodes are fabricated on top of the SiO_2 layer. The SiO_2 layer is used to create an electrical insulating layer between the electrodes and the silicon substrate. It also helps minimizing the parasitic capacitance in the circuitry.

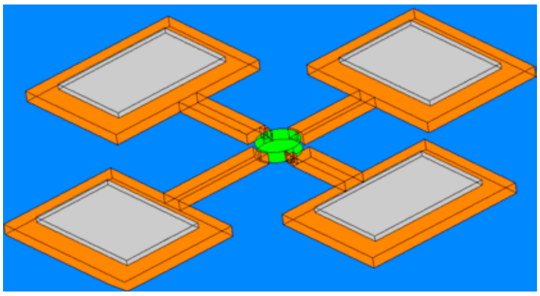


Figure 2: Schematic illustration of the chip layout with the disk (green) and the electrodes (orange). The disk and the electrodes are fabricated in poly-silicon. The contact pads (gray) are fabricated in aluminum.

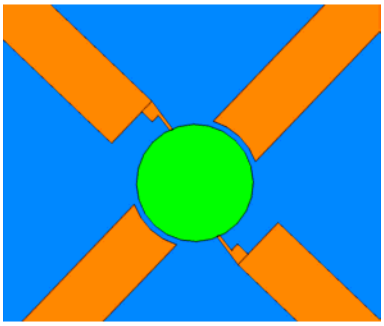


Figure 3: Schematic illustration of the disk (green) and the electrodes (orange) seen from above. The disk and the electrodes are fabricated in poly-silicon. The contact pads (gray) are fabricated in aluminum.

Electrical charges are supplied to the disk through the anchor points. Furthermore, the anchoring is used to provide mechanical stability to the resonator.

The fabrication process of the microdisk resonator basically consists of applying three masks.

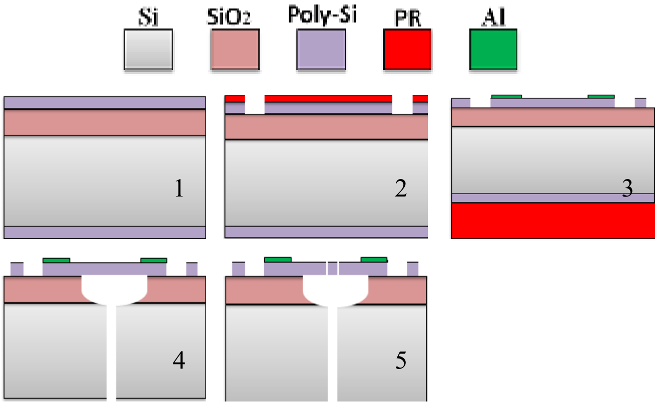


Figure 4: Schematic illustration of the fabrication process for the microdisk resonator. The following abbreviations are used: Silicon (Si), silicon dioxide (SiO_2), poly-silicon (Poly-Si), photoresist (PR) and aluminum (Al).

1) Silicon dioxide and poly-silicon layers are deposited on a silicon substrate.
2) The first mask is used to define the poly-silicon layer.
3) Metallization on front side to define contact pads.
4) Backside etching to oxide etches stop, then substrate HF etching to release the poly-silicon structure.
5) The FIB method is used to release the disk (see figure 5).

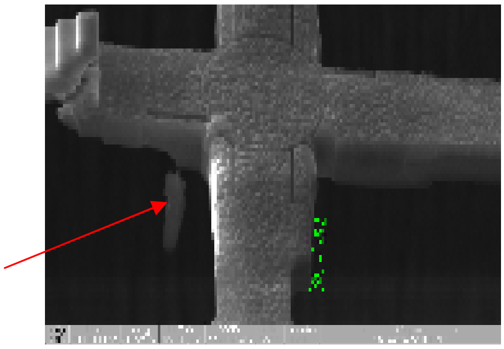


Figure 5: The four "arms" are defined by the FIB beam, but because of the thick silicon dioxide layer the milling did not work and the disk is not released. The red arrow shows that some parts of the electrode would fall off if the silicon dioxide was not present.

4. Simulation Results

One of the basic equations that characterize the property of a bulk mode resonator is the equation of motion given as:

$$m_{re}\cdot\frac{d^2x}{dt^2}+c\frac{dx}{dt}+k_{re}\cdot x=F_{external}(x,t) \qquad (1)$$

Where m_{re} is effective mass of the system, c is the damping factor that takes into account the losses of the system, k_{re} is stiffness constant and $F_{external}$ is the applied force.

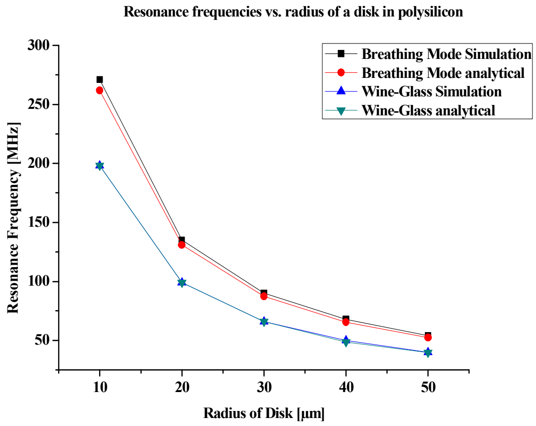


Figure 6: Resonance frequency as a function of disk radius for a circular disk. The resonance frequency decreases as the disk radius increases.

The system is excited by the external force, which is a time dependent sinuous force. This system can only be solved analytically for very simple geometries. To build a model for the mechanical properties of more advanced resonator geometries numerical methods have to be applied, making COMSOL a valuable tool in the characterization and optimization of the geometry of microdisk resonators.

However, the fabrication methods used impose some limitations on the physical design.

When the FIB method is used there is no possibility to anchor the disk in the middle and the resonator must be anchored at the semi-stationary quasi-nodal points at the periphery. In that way, the damping loses are thought to be minimized. The charges are supplied to the disk through the anchor points. Furthermore, the anchoring is needed for mechanical stability.

5. Discussions

The breathing mode for a microdisk resonator is found to have a higher resonance frequency than the wine-glass mode.
However, as it is easier to fabricate a resonator for the wine-glass mode it is often preferable.
A model was developed and Eigen frequency analysis, frequency response simulation, transient simulation and ellipse optimization was performed. The static capacitance and parasitic capacitance were calculated and used to optimize the disk resonator.

For the comparison the mass responsitivty of the disk and the ellipse. The calculation of $\underline{m_{re}/f}$ of is shown in figure 7. When Epar value is 1 the structure is a circle. From this point we can read the effective mass over resonance frequency for the lowest Epar value which in this case is an ellipse structure.
The best geometry was found to be an ellipse with a ratio m_{re}/f 4 to 5 times lower than for a circular disk (see figure 7). This geometry will have a high resonance frequency.

A template chip were designed and fabricated. The FIB method was applied, unfortunately it was found that all oxide was not completely etched (see figure 5), which made it difficult to do FIB experiments. No physical devices could be optimal due to a minimum thickness of 7µm imposed by the fabrication techniques.
The problem could be in the etching process of silicon dioxide. One explanation could be that a bubble inside the etch channel shielded the oxide from the etching process. Therefore, the HF acid did not etch completely through the silicon dioxide layer.

One way to solve this problem is to use a special HF containing mix with reduced surface tension, thus reducing the chance of bubble formation.

Another option is to combine the etching of the backside with a KOH etch technique. First a KOH etch is performed which gives an isotropic profile etching structure in the bottom of the chip and then ASE etch to get a channel.

6. Conclusions

We aimed to design, fabricate and simulate the performance of different types of resonators. To summarize:

1) A template chip usable with FIB was designed and fabricated. The design has 4 electrodes with a square where the FIB can mill out a milling pattern like the disk and the electrodes and the anchors that are required for a wine-glass mode resonance frequency.

2) The template chip can be altered to the wanted geometry by use of FIB.

3) FIB was used for patterning the disk, electrodes and anchors. A milling technique using the FIB was developed.

4) A simulation program was developed in COMSOL to simulate the electro-mechanical behavior of bulk type resonators. It was used to test different geometries and actuations techniques.

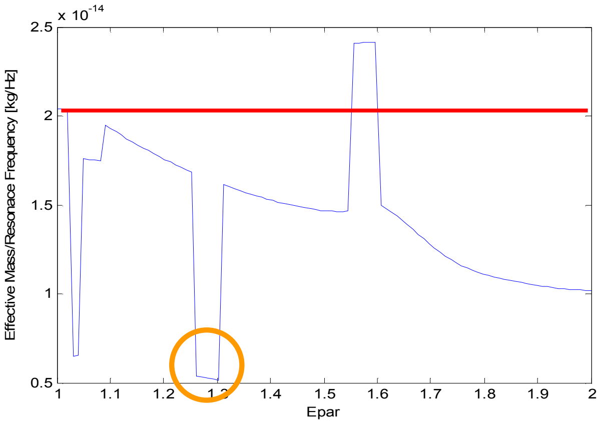


Figure 7: Epar is the ratio between the major and minor axis in the ellipse and is used as geometry-parameter going from 1 to 2. On the y axis is the effective mass divided by resonance frequency. In the small ellipse the sensitivity is around 10^{-16} , with increasing device sizes the sensitivity also increases to around 10^{-14} . The red line is the mass response for a circle. The mass response is shown for a polysillicon structure with a radius of 10µm

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