Ring-shaped PZT Film Resonator for Bio-sensing Applications in Liquid Environment

Dong F. Wang\textsuperscript{a,b,*}, Xiaoqiang Li\textsuperscript{a}, Jian Lu\textsuperscript{b}, Takahisa Sagawa\textsuperscript{a}, and Ryutaro Maeda\textsuperscript{b}

\textsuperscript{a}Micro Engineering & Micro Systems Laboratory, Ibaraki University (College of Eng.), Hitachi, Ibaraki 316-8511, Japan
\textsuperscript{b}Research Center for ubiquitous MEMS & Micro Engineering (UMEMSME), AIST, Tsukuba, Ibaraki 305-8564, Japan

Abstract

This work reports a novel design of a ring-shaped PZT film resonator for bio-sensing applications in liquid environment. The ring-shaped resonator reacts with a mass perturbation to provide eigenstate (frequency) shifts which could transfer to electrical signals by piezoelectric effect of PZT. The aforementioned resonator is mainly comprised with a multilayer of Pt/Ti/PZT/Pt/Ti/SiO\textsubscript{2} deposited on the silicon-on-insulator (SOI) wafer and expected to be used at a contour mode. In order to estimate the sensitivity of the ring-shaped resonator against the mass perturbation, the theoretical analysis was conducted by ANSYS from two aspects including: a) the viewpoint of geometrical design and b) the mass application methodology. When a mass perturbation (i.e., a liquid droplet) of 10 ng is homogeneously contacting on the top insulation layer of the resonator, frequency shifts from 2.11 to 4.07 kHz could be obtained when excited in the contour mode.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: Ring-shaped resonator; Eigenstate shift; Mass perturbation; Piezoelectric thin film (PZT); Biosensing applications

1. Introduction

The term biosensor is an analytical device which could converts biological responses into electrical signals [1]. The biological responses are mainly including the concentration of substances and other parameters of biological interests. In recent years, the film bulk acoustic resonator (FBAR) had been attracted increasing considerations in the field of microwave circuits and finds its potential for biosensor application. Unlike quartz crystal microbalances, which is one of the most commonly used biosensors, the physical miniaturization of FBAR allows it could be fabricated in batch by Micro Electro Mechanical Systems (MEMS) technology. Generally, FBAR typically consists of a sandwich structure in which a

\* Corresponding author. Tel.: +81-294-38-5024; Fax: +81-294-38-5047. 
E-mail address: dfwang@mx.ibaraki.ac.jp.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
suspended piezoelectric thin film of ZnO or aluminium nitride (AlN) by two metal electrodes. The thin film of piezoelectric materials allows the ring-shaped biosensor to response a high resonant frequency (up to 10 GHz) and also the large frequency sensitivity to a mass loading (> 1000 Hz cm² / ng).

C-reactive proteins (CRP) are found in the blood, the level rising of which in response to certain tissue inflammation (i.e. C-reactive protein is an acute-phase protein) as well as rapid angiogenesis of tumors. Therefore, it is believed that effective and sensitive detection of CPR levels in blood has great potential in the application of healthcare field.

In Xu et al.’s study [2], an acoustic resonator of high quality factors (Qs) was reported. Ring-shaped piezoelectric AlN thin film was made as FBAR. The resonator was characterized by an aptamer-thrombin binding pair for a biosensor and showed a mass resolution of 1.78 ng/cm². In this work however, we study the eigenstate shift in resonant frequency due to a mass perturbation in a proposed ring-shaped PZT film resonator, and shows a rapid and competitive sensitivity, apart from the miniaturization of resonator device itself.

2. Model design of ring-shape resonator by ANSYS simulation

Figure 1 shows the basic structure of ring-shaped PZT film resonator. The resonator is consisted of SiO₂, Si, PZT, Pt and Si layers. PZT film is worked as the piezoelectric material to generate electric signals in response to the mass resonation. On the both sides of PZT film, Pt layers were used as electrode to collect and transfer the electric signal from PZT film. A silicon substrate with thickness of 2 μm was used to support all the films of electrodes and PZT.

![Fig. 1: a) The proposed ring-shaped PZT film resonator for bio-sensing applications in a liquid environment; b): The model for theoretical analyses by using commercial ANSYS software; c): The definitions of length L, width W, R₁, and R₂, in geometrical design.](image)

The model for theoretical analyses and the definitions of geometrical sizes are shown in Figure 1(b) and (c), respectively. The ring has the inner and outer diameter of R₁ and R₂ (≤ 100μm). Therefore, the width of the ring could be described as W=R₂-R₁. There is also a support which is fixed and the length of this support is described as L. Obviously, the frequency shift of the ring-shaped resonator is affected by both factors of L and W. In order to estimate the sensitivity to small mass perturbation of the eigenstate (resonant frequency) of the ring-shaped resonator, theoretical analysis has been conducted for eigenstate shifts with and without small perturbation using ANSYS software.
3. ANSYS simulation results and discussion

In order to examine the possibility of testing the small mass perturbation by the ring-shaped resonator, 10 and 20 ng water were assumed put on the top of this ring-shaped resonator, thereafter, a driven force was supplied and then the data of frequency shift was obtained by ANSYS results. That is, the obvious frequency shift results in great significance in testing of the small mass perturbation.

There are various frequency behaviours existing on the ring-shape resonator, however, 5 different and typical frequency modes were discussed in this work. As shown in Figure 2 b), there are the eigenstate shifts in vibration Mode 1 to Mode 5 (shown in Figure 2 a) as a function of length, before and after a mass perturbation of 10 ng was induced. With the increasing of the ring-handle length, the frequency shift presents a downtrend in the data-graph. Especially on Mode 3, the frequency shift dropped about 5 kHz when the length of ring-shaped resonator changed from 0.14 to 0.56 of Length/R2. On the vibration Mode 1 and 2, the frequency shifts were mostly the same as the length changed.

Figure 2 c) shows eigenstate shifts in vibration Mode 1 to Mode 5 as a function of width, before and after a mass perturbation 10 ng was induced. Unlike the affection of handle length, with the increasing of ring width, all of the 5 modes had the significant downtrends. The most obvious downtrend was present in Mode 5 that the frequency shift decreased from 37 kHz to 18 kHz when the width of ring-shaped resonator increased from 0.14 to 0.78 of width/R2.

Therefore, Mode 5 became the most potential alternative for the further research of manufacture by MEMS technology. There are two obvious advantages of using Mode 5 as our destination: 1) the frequency shift against the mass perturbation of 10 ng is the most significant and 2) the vibration behaviour of Mode 5 is the most stable manner which benefits to harvest the stable signals outputting and prolong the operating life of the ring-shaped resonator.

![Fig. 2: a) Frequency shift as a function of length, with a relation to different vibration modes; b) Frequency shift as a function of length, with a relation to different vibration modes; and c) Frequency shift as a function of width.](image)

The frequency shifts from 2.11 to 4.07 kHz can then be obtained when excited in the contour mode. Figure 3 a and b) show the frequency shifts in vibration Mode 1 and Mode 4, respectively, due to the mass perturbation as a function of R1 as defined in Figure 1 c). The monotonous behaviour of frequency shift in Mode 4 can be qualitatively explained by Equation (1), where R1 and R2 are the inner and outer radii of the ring, and E and ρ are the Young’s modulus and density of silicon respectively. However, the extreme point is derived for optimum design as observed in Figure 3 a).

\[
f_0 = \frac{1}{2\pi \sqrt{R_1 R_2}} \sqrt{\frac{E}{\rho}} \tag{1}
\]
In light of the above analyses, the structural design of the ring-shaped resonator has been achieved and the prototype devices will be fabricated from multilayer of Pt/Ti/PZT/Pt/Ti/SiO$_2$ deposited on silicon-on-insulator (SOI) wafers using a 5-mask micromachining process, as shown in Fig. 4. Comparison between empirically observed shifts in resonant frequencies and theoretical estimates will be conducted afterwards.

4. Conclusion:

The novel design of the ring-shaped resonator based on PZT film was made and the resonator was aimed to manufacture biosensor which could be utilized in liquid environment. The capability of the resonator that responding to small mass perturbation of liquid media was simulated and tested by ANSYS software, based on various parameters of ring-handle lengths and ring widths. The results indicated that when a mass perturbation (i.e., a liquid droplet) of 10 ng was homogeneously contacting on the top insulation layer of the resonator, frequency shifts at least from 2.11 to 4.07 kHz could be obtained.

References

[1] Yan Z, Zhou X, Pang G, Zhang T, Liu W, Cheng J, Song Z, Feng S, Lai L, Chen J, and Wang Y. ZnO-based film bulk acoustic resonator for high sensitivity biosensor applications. Appl Phys Lett 2007; 90: 143503-5.

[2] Xu W, Choi S, and Chae J. A contour-mode film bulk acoustic resonator of high quality factor in a liquid environment for biosensing applications. 2010; 96: 053703-053705.