Optimization of Piezoelectric Pattern Design in Ring-shaped Resonators for Health-care and Environmental Applications

Dingkang Wang, Man Yu, Dong F. Wang, Toshihiro Itoh, Ryutaro Maeda

Abstract

A ring-shaped piezoelectric resonator was proposed for health monitoring. The proposed ring-shaped resonator is comprised with a multilayer of Pt/Ti/PZT/Ti/Pt/SiO₂, deposited on the silicon-on-insulator wafer and expected to be a contour mode. The ring-shaped resonator reacts to certain voltage vibration with a mass perturbation to get eigenstate vibration or frequency shifts which could be transferred to electrical signals by piezoelectric effect. In this paper, vibration modes with high frequency shift due to a small mass perturbation of 0.74 ng are analyzed. It is found that the relatively lower displacement at the support can be obtained, and the desirable vibration can be reproduced with two eigenstate modes.

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Keywords: Optimization; Piezoelectric pattern design; Ring-shaped resonator; Eigenstate shift; Mass perturbation; Bio-sensing applications

1. Introduction

In recent years, the film bulk acoustic resonator (FBAR) has attracted increased attention in the field of microwave circuits and realized some of its potential for biosensor applications. Unlike quartz crystal microbalances,
which is one of the most commonly used biosensors the physical miniaturization of FBAR allows it to be fabricated in batch by Micro-Electro-Mechanical-Systems (MEMS) technology. Generally, FBAR typically consists of a sandwich structure in which a suspended piezoelectric thin film of ZnO or aluminum nitride (AlN) by two metal electrodes.

Until now, various types of MEMS resonator have been reported. Among them, the disk-shaped resonators were most intensively investigated. However, the disk-shaped resonator suffers from small amplitude and requires precise fabrication. As their size is smaller, the disk-shaped resonators decrease vibrating amplitude rapidly, resulting in decreasing electrical signal. Therefore, they tend to require complicated amplification circuits for high frequency applications. In addition, the performance of the disk-shaped resonators is sensitive to misalignment in fabricating a support positioned at the center of a resonant disk. When misalignment occurs, unnecessary vibration modes are generated, resulting in complicated resonator vibrations. Especially in the application of liquid environment, the disk-shape would influence the vibration mode dramatically because the mass perturbation of liquid molecules is hardly to be changed on a very large surface area but a thin layer of resonator.

Similar in mass, the ring-shaped resonator has a larger size compare to disk-shaped resonator, and this can prolong the vibration amplitude and acquire a more stable single. Besides, the ring-shaped resonator is less sensitive to the misalignment of the support. We can also ensure the axiality of the resonator and the droplet if the inner ring and the outer rings manufactured at the same center. In the end, we can elevate the ration of the thickness and the area by setting the size of the ring surface.

Ring-shaped resonators were developed into such applications in liquid environment to overcome problems of disk-shaped resonators. For example, 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 [1]. The resonator was characterized by an aptamer-thrombin binding pair for a biosensor and showed a mass resolution of 1.78 ng/cm².

Support loss is another point to be considered. In Hao et al.’s study [2], the support loss in micro machined beam resonators was discussed with in plane vibrations by using 2D elastic wave theory. Another study [3] further discussed the support loss in disk resonator.

In contrast with our past studies [4-6] focusing on the effect of the ring geometry and support geometry, this work puts the emphasis upon the effect of the PZT pattern of the piezoelectric layer on eigenstate shift in resonant frequency and support loss (from view point of vibration mode shape) due to a mass perturbation in a proposed ring-shaped resonator.

Table 1 Thickness of each layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
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<tbody>
<tr>
<td>Si</td>
<td>2 μm</td>
</tr>
<tr>
<td>SiO₂</td>
<td>0.3 μm</td>
</tr>
<tr>
<td>Pt</td>
<td>0.2 μm</td>
</tr>
<tr>
<td>PZT</td>
<td>1 μm</td>
</tr>
<tr>
<td>Pt</td>
<td>0.2 μm</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1 μm</td>
</tr>
<tr>
<td>Si</td>
<td>1 μm</td>
</tr>
</tbody>
</table>

Fig. 1 Simulation model constructed in present study, comprised of Pt, PZT, SiO₂, and Si substrate.
2. Design of piezoelectric pattern/Proposal of PZT pattern

The proposed ring-shaped resonator is comprised of SiO₂/Pt/PZT/Pt/SiO₂/Si layers (Fig. 1), and then antibody-CRP is assembled on the top surface to catch the CRP. The resonator consists of SiO₂, Si, PZT-Si, Pt and Si layers, Table 1 gives the thickness of each layer. The resonator. SiO₂ and Pt are respectively insulation layer and electrode layer. PZT film is worked as the piezoelectric material to generate electric signals in response to the mass resonation.

The silicon based PZT layer was sandwiched between the two Pt layers. Pt layers were used as electrode to collect and transfer the electric signal from PZT film. PZT takes part of the area of Si wafer basement (Fig. 2) in the designed pattern with the art describe in [7]. A silicon substrate with thickness of 2 μm was used to support all the films of electrodes and PZT.

In the design of PZT pattern, the first thing to be noted is as the wafer of PZT is composed of small pieces of (single crystal silicon), the geometry of PZT should be in the same size of the single wafer so that the PZT and the silicon basement can have a good coupling. The miniaturization of PZT pattern means the total area of the PZT should be downsized, in order to enhance the sensitivity and lower the loading effect. Besides, the PZT pattern should be kept away from support, to avoid support displacement and deformation. Also, to achieve a balanced vibration mode, the PZT pattern should be symmetric with the ring.

In the model for theoretical analyses, PZT is embedded in the silicon based layer. The silicon layer is composed of small wafer. PZT is placed symmetrically in different radios. We define the parameter, the two positions as follow in Fig. 2, Position 1 is in the direction of support, and Position 2 is in the 45° direction of the support.

![Fig. 2 The position and size parameters of the PZT patterns](image)

3. Simulation results and discussion

In order to examine the possibility of testing the small mass perturbation by the ring-shaped resonator, 10 and 20 pg liquid were assumed put on the top of this ring-shaped resonator, thereafter, a driven force was supplied and then the data of frequency shift (ring) and vibration mode shape (support) were obtained by simulation analysis.
Fig. 3 Intrinsic modes of the ring shaped resonator and their ANSYS simulation

There are various frequency behaviors existing on the ring-shaped resonator, seven vibration modes are found from low frequency to high frequency, this is the intrinsic mode of the ring resonator without different shape of PZT on it. This is called the eigen state frequency of the resonator.

Not all the eigen states will have a good performance of high sensitivity and quality factor. Support loss is the key factor that will severely decrease the quality to an unacceptable level. Support loss is defined as the product of stress of the support and stress of the support.

As a result, we choose Mode 1, Mode 2 as our simulation modes as shown in Fig. 3.

4. Conclusions

The ring-shaped resonator based on PZT film for health-care and environmental applications was proposed and analytically studied using ANSYS software, focusing on the effect of PZT pattern on frequency shift and support loss. Among the several eigen vibration modes, this study demonstrated that support displacement of Mode 1 and Mode 2 is smaller the so those two vibration modes show a higher Q-factor.

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References


