Piezoelectric Lead Zirconate Titanate (PZT) Ring Shaped Contour-Mode MEMS Resonators

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Abstract. Flexibility in setting fundamental frequency of resonator independent of its motional resistance is one of the desired criteria in micro-electromechanical (MEMS) resonator design. It is observed that ring-shaped piezoelectric contour-mode MEMS resonators satisfy this design criterion than in case of rectangular plate MEMS resonators. Also ring-shaped contour-mode piezoelectric MEMS resonator has an advantage that its fundamental frequency is defined by in-plane dimensions, but they show variation of fundamental frequency with different Platinum (Pt) thickness referred as change in ratio of $f_{REW}/f_o$. This paper presents the effects of variation in geometrical parameters and change in piezoelectric material on the resonant frequencies of Platinum piezoelectric-Aluminium ring-shaped contour-mode MEMS resonators and its electrical parameters. The proposed structure with Lead Zirconate Titanate (PZT) as the piezoelectric material was observed to be a piezoelectric material with minimal change in fundamental resonant frequency due to Platinum thickness variation. This structure was also found to exhibit extremely low motional resistance of 0.03 $\Omega$ as compared to the 31-35 $\Omega$ range obtained when using AlN as the piezoelectric material. CoventorWare 10 is used for the design, simulation and corresponding analysis of resonators which is Finite Element Method (FEM) analysis and design tool for MEMS devices.

1. Introduction

Micro-Electro-Mechanical Systems (MEMS) is a technology which integrates electrical and mechanical elements to create devices whose dimensions are in the range of micrometers to millimeters. If broadly classified, the types of MEMS devices can vary from relatively simple structures involving no moving elements to extremely complex systems with multiple moving elements. MEMS devices are capable of performing many of the same tasks as macroscopic devices while also providing added advantages, most notably miniaturization of the system, easy integration into existing systems and convenience of mass fabrication of arrays of devices [1][2][3].

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The ever increasing demand for radio-frequency (RF) filters in modern day electronic devices has shifted research focus towards reducing size, power consumption and fabrication cost of microelectronic structures. Vibrating contour-mode resonators prove to be an efficient solution to realizing these objectives, thus generating noteworthy research and commercial interest. They are poised to capture a significant portion of the MEMS market in the near future owing to their high Q factor and low motional resistance [4].

Motional resistance of a resonator has a very important role. If the motional resistance is high, high terminating external resistance is required to reduce the pass-band ripples. Brownian noise is directly proportional to the motional resistance of the resonator. If a resonator with high motional resistance is used as an oscillator, an amplifier with very enormous gain will be required in order to compensate the damping caused by the resistance. Resonator with high motional resistance may limit the highest attainable resonant frequency for a given circuit technology [5].

In the past, very high resonant frequencies have been obtained using polysilicide resonators. But the motional resistance of these resonators is extremely high, of the order of hundreds of kΩ which is undesirable. Thus piezoelectric materials were experimented for resonators, the motional resistance of these were found to be much lower than the earlier designs [6]. The configurations in which piezoelectric materials were used were Surface Acoustic Wave (SAW) [7] and Film Bulk Acoustic Wave Resonators (FBAR) [8].

This paper touches upon aluminium nitride and PZT piezoelectric resonators, aptly named contour-mode resonators due to their fundamental frequency being governed by the in-plane dimensions of the device. The contour-mode resonators have the advantage of low motional resistance and their resonant frequency does not depend on the thickness of piezo layer, unlike SAW and FBAR. Hence, mass production of resonators was possible due to contour-mode design as the resonant frequency of devices could be varied by changing the horizontal dimensions i.e. by varying the width and shape of resonating structure keeping thickness of piezo same instead of vertical dimensions. This saves time and is cost effective as different resonance frequencies can be obtained in a single batch of fabrication. These dimensions are varied with the help of computer-aided design (CAD) layout available in CoventorWare suite [4].

In ring structures, more flexibility is offered in terms of low values of motional resistance (less than 200 Ωs) being set independently than in the case of the rectangular plate for which a fixed aspect ratio must be maintained [4]. Thus ring-shaped structures have been preferred while designing over rectangular plate resonator designs.

The remaining paper is described as follows. The design of ring-shaped contour-mode resonator model is explained in Section 2, the process flow for fabrication of ring-shaped contour mode resonator with PZT as piezoelectric material is explained in Section 3, dimension variations in Section 4 followed by results and conclusion in Sections 5 and 6 respectively.

2. Ring-shaped Contour-mode resonator model
The solid 3-D model of piezoelectric ring-shaped resonator with piezoelectric vibrating material is as shown in figure 1. The piezoelectric material is sandwiched between two electrodes, namely Aluminium (Al) and Platinum (Pt) electrodes. The Al electrode is the input electrode whereas the Pt electrode acts as the ground electrode. Aluminium was selected as the input electrode instead of Platinum as Aluminium layer thickness does not cause significant frequency shift in the resonant frequency spectrum of the resonator. Platinum was used as output electrode due to its high conductivity, which is essential as only a particular signal is passed and its amplitude might be low, so unnecessary attenuation of the signal, is avoided. Pt could have been used as an input electrode as well.
but it is expensive and introduces frequency shift, hence Al is preferred over it. The electric field applied between these two electrodes provides the necessary stimulus for the structure to vibrate across its width. In this structure, the entire top surface is made to act as an electrode. The advantage of this topology is the minimization of undesired modes of vibration thus leading to maximum energy getting coupled into the desired mode. Another benefit of such a design is the motional resistance is obtained of minimal values.

3. Process Flow

![Figure 1. 3-D model of ring-shaped contour-mode micromechanical resonator with top surface as Input Electrode (Al) and bottom surface as Ground Electrode (Pt) [4].](image)

![Figure 2. Process flow for fabrication proposed of ring-shaped contour mode resonator with Lead Zirconate Titanate (PZT) as piezoelectric material (a) Starting p type Silicon 100 orientation wafer (b) Si wafer wet etch (Mask1) (c) A thin film of Platinum deposition and patterning (Mask2) (d) Deposition of Boronphosphosilicate glass (BPSG) as sacrificial layer (e) & (f) Lead Zirconate Titanate (PZT) and Aluminium metal layers deposition and patterning (Mask3) (g) Sacrificial layer removal](image)

The cross-sectional view of process fabrication steps for ring-shaped contour-mode MEMS resonator with PZT as piezoelectric material is as shown in figure 2. To model these resonators, fabrication process steps are defined in MEMS design and simulation software platform CoventorWare. It is a three mask process. These mask layouts are as shown in figure 3. A Silicon (Si)
wafer with (100) orientation is a starting substrate material. The portion of this silicon substrate is then etched away by wet chemical etch using KOH with Mask 1. A thin film of Platinum metal layer is then deposited on this substrate using Chemical Vapour Deposition (CVD) and patterned by Chlorine Reactive Ion Etching (RIE) using Mask 2. A compound known as Boronphosphosilicate glass (BPSG) is then deposited using APCVD / LPCVD process as a sacrificial layer. Lead Zirconate Titanate (PZT) and Aluminium metal layers are then deposited using metal organic CVD and sputtering process respectively. Both these layers are then patterned and given the desired shape of ring using Inductively Coupled Plasma Reactive Ion Etching (ICPRIE) [9] [10]. During the patterning of these two layers, Titanium Aluminium Nitride (TiAlN) is used as a mask layer. The BPSG layer is then removed using wet chemical etch process leaving behind the desired structure. However, the fabrication process steps using AlN as piezoelectric material is different than PZT which is not discussed here.

Figure 3. Ring-shaped contour-mode MEMS resonator mask layout as observed in CoventorWare10 with width of the resonator ring as 20 um.

Figure 4. Ring-shaped contour-mode MEMS resonator mask layout as observed in CoventorWare10 with width of the resonator ring as 60 um (other dimensions =are same as given in Figure 3).

Figure 5. 3D model of ring shaped contour mode resonator with width of the inner radius as 60 um.

4. Dimension Variations
In order to see the effect of variations in geometrical parameters namely inner radius of the ring on the resonant frequency and electrical parameters of ring-shaped contour-mode piezoelectric MEMS resonator, different mask layouts are used. The mask layouts are as shown in figure 3 and figure 4. The representative 3D model of the same for 60 µm inner radius is shown in figure 5.
Also, in the fabrication process steps of these resonators, Pt may not be deposited uniformly over the entire substrate due to inherent nature of the deposition process. In order to address this effect of change in thickness of Pt electrode on the resonant frequency of the PZT ring-shaped resonator, the Pt thickness was changed between 100 nm to 400 nm. The representative 3D models of the same for 100 nm and 400 nm are as shown in figure 6 and figure 7 respectively.

Figure 6. 3D model of the proposed ring-shaped contour-mode MEMS resonator with thickness of Pt layer maintained at 100 nm.

Figure 7. 3D model of the proposed ring-shaped contour-mode MEMS resonator with thickness of Pt layer increased to 400 nm.

5. Results

For simulation and result analysis, PZT and AlN are selected as piezoelectric materials for proposed resonator. The unloaded centre frequency $f_o$ of piezoelectric material is governed theoretically by the equation (1).

$$f_o \approx \frac{1}{2W} \sqrt{ \frac{E_p}{\rho(1-\sigma^2)}}$$  \hspace{1cm} (1)

where $W$ is the width of the ring, $E_p$ is the Young's modulus of the piezoelectric material, $\sigma$ is the mass density of the piezoelectric material, and $\rho$ is the Poisson's ratio of the piezoelectric material.

The resonant frequency of the proposed resonator is obtained using simulation and analytically by equation (1) for both the piezoelectric materials. The results are shown in table 1.

Table 1. Variation of resonant frequency with variation in width of the ring of Aluminium Nitride and Lead Zirconate Titanate (PZT) ring-shaped contour-mode MEMS resonator

| Width (µm) | Aluminium Nitride | Lead Zirconate Titanate |
|------------|-------------------|------------------------|
|            | Calculated        | Simulated              | Calculated | Simulated |
| 20         | 259.10            | 246.02                 | 88.64      | 98.70     |
| 40         | 129.55            | 124.72                 | 44.20      | 49.90     |
| 50         | 103.64            | 100.67                 | 35.36      | 40.50     |
| 60         | 86.36             | 85.30                  | 29.47      | 33.86     |

It is observed from table 1 that the results obtained using simulation nearly matches to the calculated values and hence confirms the simulation results. The horizontal mode of vibration of the contour-mode design as observed in CoventorWare is as shown in figure 8 as a representative mode of vibration.
During the fabrication of this resonator, it is possible that the deposition thickness of the Pt and Al electrodes is non-uniform as mentioned in Section 4. However, the effect of mass loading on the resonant frequency of this MEMS resonator i.e. the change in fundamental (centre) resonant frequency is dominated by the Pt electrode thickness and that of Al electrode thickness can be neglected [1]. This is given in equation (2).

\[ f_{\text{NEW}} \approx f_0 \sqrt{\frac{1+\frac{\rho PL A_p}{\rho P E_p} + \frac{\rho MAP}{\rho P E_p}}{1+\frac{\rho MAP}{\rho P E_P}}} \]  

(2)

where \( f_0 \) is the unloaded resonant (centre) frequency, \( E_p \) is the Young's modulus of the piezoelectric material, \( \rho_p \) is the mass density of the piezoelectric material, \( A_p \) is the area of the piezoelectric material, \( E_{Pt} \) is the Young's modulus of the platinum material, \( \rho_{Pt} \) is the mass density of the platinum material, \( A_{Pt} \) is the area of the platinum material. Using equation (2) and plugging in the values of Young's modulus, mass density and poisson's ratio of AlN, PZT, Pt, Al, the resonant frequencies of the designed piezoresonators were calculated and compared with the simulation results in CoventorWare 10. These variations of \( f_{\text{NEW}}/f_0 \) for Pt thickness ranging from 100 nm to 400 nm are as shown in figure 9 and table 2.

Figure 9. Plot of \( f_{\text{NEW}}/f_0 \) vs Platinum Thickness comparing performance of PZT and AlN as piezoelectric material in ring-shaped contour-mode MEMS resonators.
It is clear from figure 9 and table 2 that PZT type resonator has less variation in $f_{NEW}/f_o$ as compared to AlN type resonator. The Young's modulus of PZT is less than AlN and mass density of PZT is more than AlN. Thus, according to the equation (2) of frequency setting, the variation in resonant frequency calculated was observed to be less.

Further the simulation of the piezoelectric contour mode ring shaped resonator for PZT and AlN is carried out in CoventorWare 10 to obtain frequency response and electrical parameters of these resonators. The electrical parameters of the resonators are extracted from the frequency response using equations (3-8) in CoventorWare. To determine the electrical parameters of resonators the electrical equivalent model of the resonator used is given in figure 10 as similar to [4].

Also the frequency response of ring-shaped contour-mode MEMS resonator with AlN and PZT as piezoelectric materials is shown in figure 11 and figure 12 respectively.

$$f_s = \frac{1}{2\pi \sqrt{\rho_c \mu_m}}$$  \hspace{1cm} (3)

$$f_P = f_s \sqrt{\frac{C_m}{C_o + 1}}$$  \hspace{1cm} (4)

$$k^2_{eff} = \frac{f_P^2 - f_s^2}{f_P^2}$$  \hspace{1cm} (5)

$$k^2_{A} = \frac{\rho \mu f_s}{2 \pi f_P tan \left( \frac{\pi f_s}{2 f_P} \right)}$$  \hspace{1cm} (6)

$$Acoustic_{A}^2 = \frac{\pi^2 C_m}{8 \pi C_o}$$  \hspace{1cm} (7)

$$Q = \frac{\sqrt{\rho_c \mu_m}}{k_m}$$  \hspace{1cm} (8)

| Platinum thickness (nm) | Resonant Frequency (MHz) |
|-------------------------|--------------------------|
| 100                     | 98.71                    |
| 150                     | 98.62                    |
| 200                     | 98.84                    |
| 250                     | 98.65                    |
| 300                     | 98.64                    |
| 350                     | 98.56                    |
| 400                     | 98.56                    |

Table 2. Variation of resonant frequency with variation in Platinum thickness of ring-shaped contour-mode MEMS resonators for PZT as piezoelectric material.
The simulated results and corresponding electrical parameters obtained for proposed MEMS resonator design for AlN and PZT piezoelectric materials are shown in table 3 and table 4 respectively.

**Table 3.** Electrical Parameters obtained for Aluminum Nitride (AlN) ring-shaped contour-mode MEMS resonator

| Parameter                          | Value     |
|------------------------------------|-----------|
| Motional Resistance $(R_m)$        | 32.34 Ω   |
| Motional Inductance $(L_m)$        | 26.19 µH  |
| Motional Capacitance $(C_m)$       | 163.38 pF |
| Series Resonance Frequency $(f_s)$ | 243.28 MHz|
| Electromechanical Coupling $k_{eff}^2$ | 0.0220 |
| $k_t^2$                            | 0.0270    |
| Acoustic $k_t^2$                   | 0.0278    |
| Parallel Resonance Frequency $(f_p)$ | 246.01 MHz|
| Supplied Q factor (Q)              | 1237.80   |
| Capacitance to Ground$(C_o)$       | 0.7 pF    |

**Table 4.** Electrical Parameters obtained for Lead Zirconate Titanate (PZT) ring-shaped contour-mode MEMS resonator

| Parameter                          | Value     |
|------------------------------------|-----------|
| Motional Resistance $(R_m)$        | 0.03 Ω    |
| Motional Inductance $(L_m)$        | 65.9 µH   |
| Motional Capacitance $(C_m)$       | 47.3 pF   |
| Series Resonance Frequency $(f_s)$ | 90.09 MHz |
| Electromechanical Coupling $k_{eff}^2$ | 0.16 |
| $k_t^2$                            | 0.19      |
| Acoustic $k_t^2$                   | 0.24      |
| Parallel Resonance Frequency $(f_p)$ | 98.71 MHz |
| Supplied Q factor (Q)              | 1217.02   |
| Capacitance to Ground$(C_o)$       | 236.24 pF |
Figure 11. Frequency response of ring-shaped contour-mode MEMS resonator with Aluminium Nitride (AlN) as piezoelectric material.

Figure 12. Frequency response of ring-shaped contour-mode MEMS resonator with Lead Zirconate Titanate (PZT) as piezoelectric material.

6. Conclusion
The limitation of ring-shaped contour-mode resonator is that the fundamental resonant frequency shifts due to variation in Platinum thickness. This drawback is overcome by using Lead Zirconate...
Titanate (PZT) as an alternative piezoelectric material for these resonators. This is assured through comparison of the results obtained by calculation of the frequency shift by analytical expression given in equation (2) and also simulation in FEM MEMS Design tool CoventorWare10. The frequency response and electrical characteristics of these resonators are obtained for various geometrical dimensions through simulation. The results show fundamental frequency of these resonators is in the range of MHz and with low motional resistance and high quality factor. In future, the resonant frequency and electrical parameters of these resonators can be obtained after fabrication and compared with simulation results to validate their use in real-life applications.

7. References
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