Characterization of a Single Port Aluminum Nitride Tuning Fork

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Abstract—In this study the characterization of an aluminum nitride (AlN) double ended tuning fork (DETF) fabricated on a layer of silicon dioxide (SiO2) is presented. The positive temperature coefficients of SiO2 are used to achieve zero TCF for radio frequency (RF) Lamb wave resonators. This paper shows the possibility to integrate temperature compensated Lamb wave resonators with DETF-based devices on a single chip. The DETF resonates in a quasi-in-plane mode shape with a Q-factor of 578 in air and 3028 in vacuum. Through a laser Doppler velocity (LDV) measurement we also show that, due to the biomorph nature of the structure and the angle of the side walls, the motion of each tine of the DETF is a combination of in-plane bending, out-of-plane bending and torsional motion around the beam main axis.

Keywords—Aluminum Nitride, Double Ended Tuning Fork, Lamb Wave Resonator.

I. INTRODUCTION

DOUBLE ended tuning forks (DETF) have been widely used as resonating elements for time reference devices [1]–[3] and for sensing applications [4]–[6]. These types of resonators are generally based on quartz for timing reference applications and on single crystal or polycrystalline silicon, for sensors. Although previous research has demonstrated good performance in terms of Q-factor and temperature stability, the integration of these elements with the integrated circuit (IC) presented several difficulties. Quartz resonators need high precision during their assembly in the package to prevent residual stresses to modify the resonator’s frequencies while the deposition of polycrystalline silicon has a temperature budget that exceeds the maximum temperature that an IC can withstand.

Recently, because of its applications in Lamb wave resonators (LWR) and bulk acoustic wave (BAW) resonators, AlN has gained increasing interest in MEMS research. Due to its post CMOS compatible fabrication process, AlN films can be a promising solution for a full integration of MEMS structures to the top of the IC. This integration would not only enable further chip miniaturization, but also improve the circuit performance by eliminating bonding connections between MEMS devices and IC. Recently it has been proved that due to positive temperature coefficients of SiO2, it is possible to obtain a zero TCF AlN LWR with a layer of SiO2 beneath the bottom electrode of the resonating structure [7], [8].

This work shows the design and the characterization of a DETF fabricated on AlN/SiO2 composite layer by which a zero TCF Lamb wave device can be fabricated on the same chip. Fig. 1 (a) shows the SEM picture of the fabricated DETF and Fig. 1 (b) shows the cross-sectional image of the AlN and SiO2 layers. Platinum (Pt) was used for the top and bottom electrodes of the DETF. The dimensions of the tines of the DETF showed in Fig. 1 (a) are 619 µm in length and 20 µm in width. As the analysis shows, the AlN-SiO2 sandwich structure generates an out-of-plane moment resulting in an out-of-plane bending and a rocking motion which are all coupled with the desired in-plane motion.

II. DESIGN

A. Double Ended Tuning Fork structure

As shown in Fig. 2, the layout of a DETF has two tines vibrating in opposite directions connected at both ends by a

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pair of anchors. This structure is connected to the ground by a pair of tethers. The anchors and the tethers are used to confine the vibration energy in the DETF structure and to minimize the dissipation of energy into the surroundings. The actuation is obtained by applying a voltage to the top and to the bottom electrode; the resulting electric field along the z-axis induces an in-plane strain via the piezoelectric strain coefficient $d_{31}$. As shown in Fig. 2, in order to maximize the transduction area, the width of top electrode is about half of the width of the beam.

A key to enhance the performance of DETF is to minimize the energy losses and obtain high $Q$. The $Q$-factor is the result of many energy loss mechanisms that affect the beam dynamics. Each energy loss mechanism has different origins and can be minimized through the design of the resonator or the working conditions of the DETF. For beam based resonators, the total $Q$-factor can be expressed through (1):

$$\frac{1}{Q} = \frac{1}{Q_{\text{anc}}} + \sum_{i=1}^{n} \frac{1}{Q_{\text{air}-n} + Q_{\text{TPED}-n} + Q_{\text{SPM}-n}}$$ (1)

where the index $n$ is the number of spurious motions excited at a particular frequency, $Q_{\text{anc}}$ represents the energy lost through the anchors into the surroundings, $Q_{\text{air}-n}$ is the energy lost due to friction with air for the motion $n$, $Q_{\text{TPED}-n}$ represents the losses due to thermo piezoelectric damping (TPED), and $Q_{\text{SPM}-n}$ is the kinetic energy lost in the excitation of the $n^{th}$ spurious mode.

As this work illustrates, while the design of the tines determines the base natural frequency and the ultimate $Q$-factor set by the TPED [9], the design of the anchors and the tethers is key to minimize the energy lost due to spurious mode excitation ($Q_{\text{SPM}}$) and the energy lost in the surroundings ($Q_{\text{anc}}$) [10], [11].

B. Design of the tines and FE analysis

These types of resonators have been widely studied by using approximated analytical models based on Euler-Bernoulli or Timoshenko assumptions [2]. Although these theories enable analytical closed form solutions for the calculation of the natural frequencies, they assume that each tine is clamped at both ends and therefore the two beams are not mechanically coupled. For MEMS-scale devices, these assumptions are not always accurate: the two tines are mechanically coupled and, as this study shows, the coupling elements (or anchors) have an important effect in the overall dynamic behavior of the resonator.

Because of the complexity of the structure, in order to calculate the natural frequencies, we developed a 3D ANSYS model. The material properties considered for the AlN and SiO$_2$ layers were taken from Refs. [12] and [13], respectively. To improve the accuracy and the computational speed of the simulations, the model used 3D 20-node coupled field SOLID226 elements.

As it has been shown in previous work [2], for beam based resonators operating in vacuum the ultimate $Q$-factor is set by TPED – the value of the ultimate $Q$-factor can be therefore determined by the geometrical dimensions of the beams. The choice of the beam dimensions will therefore not only influence the base frequency but also the ultimate $Q$-factor of the DETF.

C. Design of the anchors

In the design of the DETF, it is desirable to isolate the in-plane natural frequency as much as possible from other mode shapes. If other mode shapes have a resonance frequency too close to the in-plane motion, some of the vibrating energy of the DETF may excite spurious modes, resulting in a lower $Q$-factor. In this work we show that the anchor design is a key factor to isolate the in-plane mode shape from other resonant frequencies.

Fig. 3 illustrates a finite element (FE) parametric analysis performed on the anchor length. In this analysis the anchor
length is swept from 5 µm to 70 µm; for each value of the anchor length, the algorithm performed a modal analysis to calculate the natural frequencies. Fig. 3 demonstrates that by tuning the anchor length, mode shapes loci may cross each other or abruptly diverge. For example, when the anchor length is about 30 µm, the out-of-plane motion (a) and the in-plane motion (c) cross each other at a frequency of 320 kHz; in this case, the two eigenmodes preserve their shape and with the proper electrode design can be independently excited. When the anchor length is about 18µm, the out-of-plane motion (a) and the in-plane motion (b) abruptly diverge. This behavior is called “curve veering” and it has been studied for several vibrating systems [14]. As it can be shown with a FE modal analysis at the curve veering point, the resulting mode shape of the DETF is a linear combination of the intersecting mode shapes. A “curve veering” point would make the DETF moving in-plane and out-of-plane, and consequently the $Q$-factor would approach values much lower than those set by TPED.

The parametric analysis of Fig. 3 shows that for the 619-µm-long and 20-µm-wide beams with the structural layers illustrated in Fig. 1, the optimal length for the anchor is about 30 µm. With this geometry, the FE model predicts an in-plane natural frequency of 383 kHz.

III. CHARACTERIZATION

A. Influence of pressure on frequency and $Q$-factor

We have tested the DETF under different pressures at ambient temperature. Fig. 4 shows the measured impedance of the DETF at atmospheric pressure and at 0.2 Torr. As the measurement shows, due to the air damping, the resonant frequency shifts from 373 kHz in air to 375 kHz in vacuum. The resonant frequency peak finds strong agreement with the prediction of the FE model; the error between the numerical simulation and the actual resonant peak is less than 2%.

Due to the static capacitance of the electrode layout the resonant peak shown in Fig. 4 only has 8deg of frequency shift. In order to obtain larger phase shift, the static capacitance (and therefore the top electrode area) must be minimized. Although the minimization of the metalized area of the top electrode reduces the transduction surface, it is important to note that the metalized surface close to the neutral axis generates a bending moment much smaller than the one near the external edge of the beam.

In Fig. 5, we report the measurement of the $Q$-factor as function of the pressure. As can be seen from Fig. 5, the $Q$-factor ranges from 578 in air to 3028 at 0.2 Torr at which point the DETF reaches the thermoelastic limit. The TPED model developed in [9] predicts a slightly higher $Q$-factor in the order of 3500 for piezoelectric beams. The model was developed considering ideal in-plane bending motion. According to (1), the fact that the TPED model predicts a higher value is an indication that some of the energy dissipates through a secondary out-of-plane motion and its relative TPED dissipation.

By using a FE analysis, it is possible to identify the main causes of the out-of-plane motions in the following:

- The AlN/SiO$_2$ layers form a biomorphic structure that generates an out-of-plane moment.
- Due to the fabrication process, the side walls of the DETF are not perfectly vertical. The slanted side walls create a stress gradient across the thickness of the beams that result in an out-of-plane moment.

In order to quantify the magnitude and the nature of the out-of-plane motion we characterized the DETF with a laser Doppler velocity (LDV) apparatus.

B. Influence of pressure on frequency and $Q$-factor

In order to characterize the out-of-plane motion of the DETF we used a Polytec OFV-3001 controller with Polytec OFV-511 sensor head connected to a HP3589A spectrum analyzer.

To avoid non-linear dynamic behavior, we first characterized the out-of-plane motion as function of the input voltage. As shown in Fig. 6, we show the out-of-plane motion of the tine at a frequency of 373 kHz. As the figure illustrates
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Fig. 6. Out-of-plane displacement as function of the driving voltage around 373kHz.

Fig. 7. LDV measurements along the beam width shows the out-of-plane and rocking motions of the tines.

for driving voltages above 600mV, the DETF shows a non-linear behavior. Due to the out-of-plane spring softening effect, the resonant frequency shifts by 800 Hz. In order to obtain a better characterization of the tine’s motion, we therefore used a driving voltage of 500 mV.

Fig. 7 shows the average values and the standard deviation of 18 measurements performed along the length of one of the DETF tines. The measurements were taken on three different points along the width of the tine. As evidenced by Fig. 7, the motion of the beam at the center of the cross section has an out-of-plane displacement of about 27 nm while near the sidewalls of the beam the out-of-plane displacement is -81nm on the left side and +101nm on the right side. These measurements show that the out-of-plane motion of the tine is a combination of out-of-plane bending and rocking motion around the principal axis.

In order to improve the $Q$-factor, especially at high pressure, it is therefore of great importance to minimize the excitation of out-of-plane motions. This can be achieved by optimizing the selectivity of the AlN to SiO$_2$ etching process.

IV. CONCLUSION

In this work, we have demonstrated that it is possible to obtain an AlN DETF resonating in the in-plane motion with a thick SiO$_2$ layer under the bottom electrode. The parametric FE analysis showed the importance of the design of the anchors to avoid spurious mode excitation. The FE analysis developed in this work was able to predict the in-plane resonant frequency with an error of less than 2 %. The fabricated DETF showed a $Q$-factor of 578 in air and 3028 in vacuum. The LDV measurements proved that in addition to the in-plane motion, the DETF vibrates significantly in the out-of-plane direction and the tines rock around their principal axis. This motion is caused by the intrinsic biomorphic nature of the AlN/ SiO$_2$ structure and by the slanted side walls of the tines. Higher $Q$-factors can be achieved by optimizing the etching process of AlN and SiO$_2$ layers and therefore reducing the energy dissipated in the out-of-plane vibration.

REFERENCES