Study on the Spurious Modes in FBAR Resonators with Quasi-Free Edges

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***Summary*—This work investigates the effects of spurious mode suppression in tethered thin-film bulk acoustic resonators (FBAR). In such a design, the quasi-free lateral boundary reduces the amplitude of the spurious modes as compared with conventional FBARs clamped on all sides. In order to quantify the degree of spurious mode suppression through the number of tethers at the periphery, FBAR resonators with various supporting structures were designed and characterized at 2.25 GHz. We experimentally confirmed that the quasi-free edge design not only shows a significant spurious mode reduction but also achieves a 1.06X enhancement in the electromechanical coupling coefficient (k_t^2), but at the cost of quality factor (Q) degradation caused by the increased electrical resistance.**

***Keywords*—FBAR, spurious mode, piezoelectric, aluminum nitride, acoustic boundary**

I. Introduction

Acoustic filters are the core element in current radio frequency front-end modules (RF-FEM) of multi-mode/multi-band cellular communication systems [1]. Among all the acoustic filter technologies investigated so far, bulk acoustic wave devices (BAWs) feature high quality factor (Q), compact volume, low loss, and excellent environmental immunity [2]. These characteristics have made BAW devices become one of the most popular candidates in the next generation communication system [3].

An RF filter is usually composed of multiple resonators arranged in series and shunt configurations to create the passband [4]. As the characteristic of the standalone resonator is the key to realizing a decent filter, the spurious responses in the vicinity of the targeted mode inevitably impair the performance of the filter [5]. In other words, the spurious modes from distinct resonators generate ripples in the passband and undesired response in the stopband when configured as a filter, which distorts the transmitted and received signals [6]. Thus, there are many solutions which have been studied to remove those unwanted modes from their frequency spectrum.

The spurious modes of an FBAR resonator are mainly originated from the Lamb wave scattering and mode conversion at the edge of the device [7]. To inhibit the propagation of the lateral standing waves due to the phase velocity dispersion [8], previous works have demonstrated several useful techniques, such as apodization [9] and framed top electrode [10], to minimize the reflected waves from the resonator edges. In particular, the framed top electrode designs effectively suppress the spurious mode by introducing a real wavenumber for the plate wave based on the dispersion of phase velocity. Moreover, another work has demonstrated the analytical analysis for the influence of the lateral boundary conditions (B.C.s) on the spurious modes of FBAR resonators [11], which has disclosed that a "quasi-free" lateral boundary condition could effectively mitigate the spurious modes in the frequency spectrum as compared to conventional fully clamped (FC) lateral boundary condition. The analysis on the "quasi-free" has also quantitatively explained the physics of the framed top electrode mechanism. However, framed top electrode designs require a precise control on the thickness (down to several tens of nm) to make the framed structure effective, which will increase the difficulties of the fabrication process.

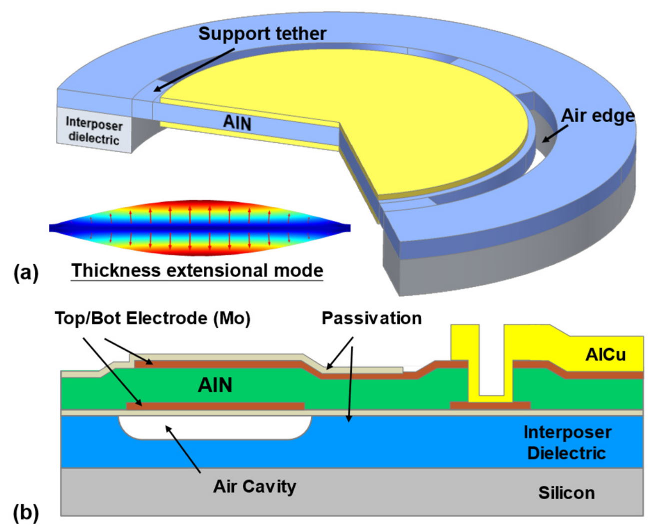

Figure 1: (a) Schematic of the proposed air edge FBAR resonator. (b) Schematic of cross-sectional view of the fabricated FBAR resonator.

In this work, we investigate the spurious mode suppression based on the concept in [11]. Instead of using framed electrodes, tethered resonators are designed to implement the quasi-free

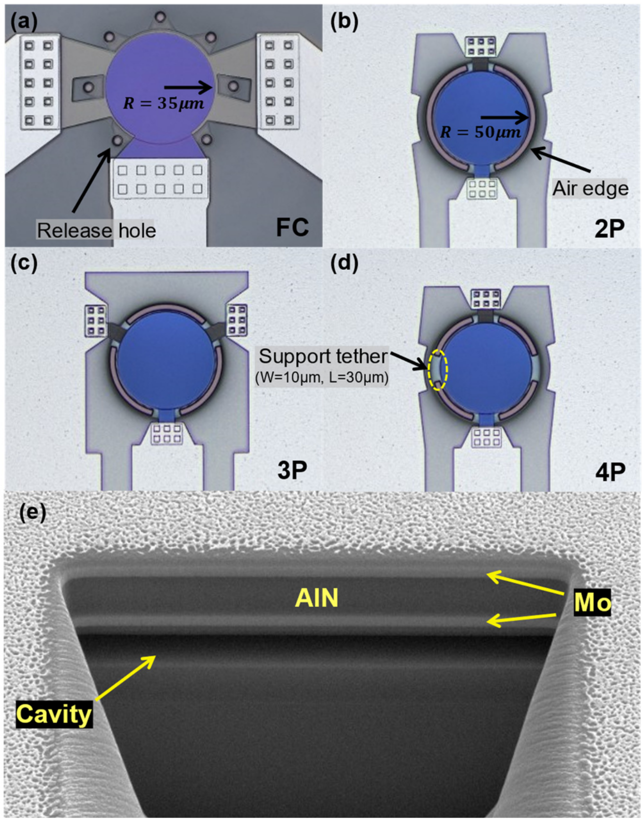

Figure 2: Optical images of the fabricated devices with (a) fully clamped, (b) two points anchored, (c) three points anchored, (d) four points anchored circular FBAR resonators, and (e) Focused Ion Beam result at the very center of the resonant disk showing that the device has been successfully released.

B.C.s through several released edges on the periphery, thereby efficiently suppressing the unwanted spurious modes.

II. Methods

Fig. 1(a) presents the schematic of the proposed air edge FBAR resonator. Unlike the conventional FBAR devices, additional AlN trenches are placed to create the air edge. The resonant disk is supported by multiple small tethers at the peripheral of the device. The staggered arrangement of the tether structure and the air edge can be regarded as a "quasi-free" boundary condition. The inset figure depicts the thickness extensional mode of the FBAR resonator. From [11], a quasi-free lateral boundary condition can significantly suppress the strength of the spurious modes. Fig. 1(b) shows the cross-sectional view schematic of the fabricated device. The FBAR is formed by a 1-μm aluminum nitride (AlN) sandwiched by the top and bottom 0.25-μm molybdenum (Mo) electrodes. Passivation layers are used to protect the electrodes during dry release steps. The overall thickness is tuned to yield the series resonance frequency (f_s) of approximately 2.25 GHz.

To verify the spurious mode suppression effect offered by the proposed air edge design, different lateral boundaries are verified in this work. First, a fully clamped device with circular electrode is designed as a control group. Later, the air edge design with different numbers of support tethers is designed to study the effect of the actual quasi-free edges on the spurious mode suppression, including two points, three points, and four points anchors, respectively.

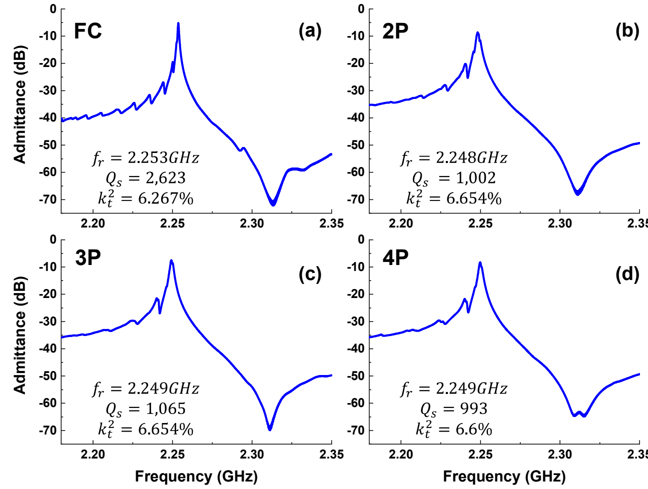

Figure 3: Frequency responses of the fabricated devices with (a) fully clamped, (b) 2 points anchored, (c) 3 points anchored, and (d) four points anchored B.C.s.

Fig. 2(a)-(d) show the optical images of the fabricated resonators with fully clamped (FC), two points anchored, three points anchored, and four points anchored circular FBAR resonators. For FC device, the radius of the resonator is around 35 μm. Large area of top and bottom Mo electrode is designed to reduce the series resistance loading effect. For air edge devices, the radius of the resonant disk is around 50 μm. AlN trench is etched out during the fabrication process to form the air edge. The width and length of the supporting tether are 10 μm and 30 μm, respectively.

III. Result and Discussion

The FBARs were measured by a Keysight E5071C VNA with a single GSG probe. The stray capacitance between the RF pads were carefully removed using an on-chip de-embedding structure. Measured admittance plots are plotted in Fig. 3. For the FC FBAR [Fig. 3(a)], the Q-factor and coupling coefficient (k_t^2) are 2,263 and 6.267%, respectively, showing an excellent figure of merit (FoM = $k_t^2 \cdot Q$) of 141 but having significant spurious modes. Fig. 4 shows the zoom-in view of the spectrum with simulated displacement of each mode. Based on the dispersion analysis, the main FBAR resonance is at the cut-off frequency of the S1 Lamb wave branch (TE). Therefore, those small ripples appeared adjacent to the desired resonance can be subsequently recognized as the laterally propagating S1 Lamb waves with non-zero lateral wave numbers.

On the other hand, the frequency responses of free-edged FBARs show significant weaker spurious modes as compared with the FC FBAR, as shown in Fig 3(b)-(d). It is evident that the spurious modes are effectively suppressed. We also observe an increased electromechanical coupling coefficient (k_t^2) through all free-edged designs, which is about 1.06 times higher than the FC FBAR (6.2% vs. 6.6%). The quality factor at the series resonance (Q_s) for free-edged designs is loaded by the

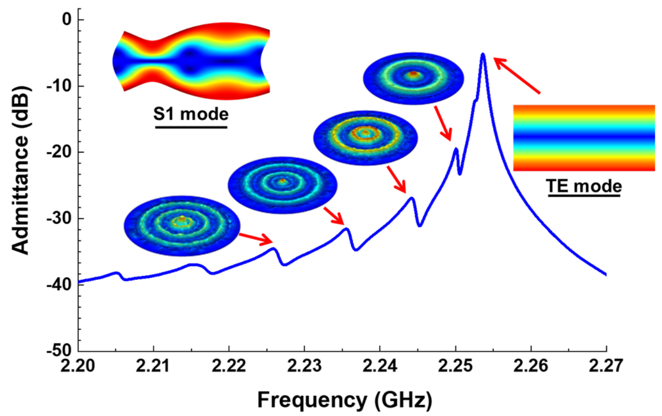

Figure 4: Zoom-in spectrum on the spurious modes of the FC FBAR with simulated displacement profiles.

series resistance (R_s) of the tether due to the narrower metal, which results in a reduced FoM.

Finally, to compare the spurious modes across different designs, Fig. 5 shows the Smith chart of the measured S_{11} with 50Ω terminal impedance. The spurious modes are shown by many small circles superimposing on the main mode (i.e., the outer circle) in the chart. A notable improvement on the spurious mode suppression before the series resonance is observed in free-edged designs. Table 1 shows the comparison between FC and proposed air edge devices with respect to resonant frequency, Q-factor, motional resistance, electromechanical coupling, and FoM. Based on Fig. 3, Fig. 5, and Table 1, the 3P anchored design seems to achieve a good balance between Q_s, k_t^2, and the suppression of spurious modes.

IV. Conclusions

This work reports the design and measurement results for the suppression of the unwanted spurious modes by anchoring the resonator using tethers. The tethered FBAR resonator features Q-factor of 1,000 and k_t^2 of 6.65% with relatively weak lateral spurious modes. The proposed concept could combine with the existing techniques to achieve further lateral mode reduction for the FBAR resonators targeted on RF front-end filters.

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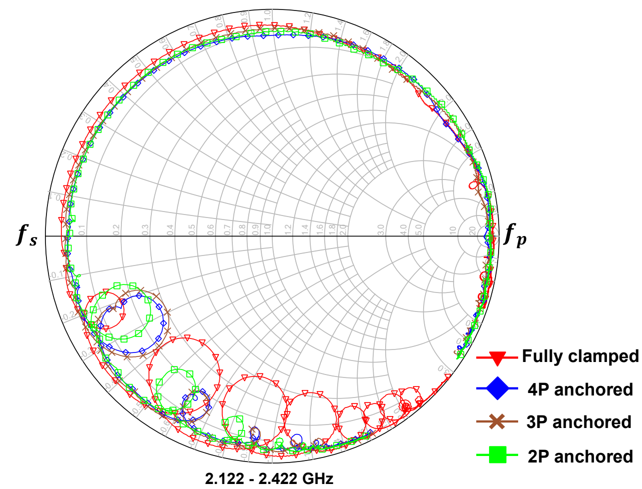

Figure 5: Smith chart of four devices shows illustrious enhancement on the suppression of the spurious mode in the spectrum.

Table 1: Comparison between FC and air edge devices in this work.

	FC	2P	3P	4P
f_s (GHz)	2.253	2.248	2.249	2.249
Q	2,623	1,002	1,065	993
R_m (Ω)	1.81	2.73	2.368	2.59
k_t^2	6.267%	6.654%	6.654%	6.6%
FoM (k_t^2*Q)	164.38	66.67	70.86	65.53

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