A Novel Approach to Integrate Multiple Film Bulk Acoustic Resonators (FBAR) with Different Frequencies in a Single Chip

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ABSTRACT

An approach of integrating multiple film bulk acoustic resonators (FBAR) with different frequencies is presented. Conventional FBAR structures were modified by adding a patterned tuning layer on top of Metal/AlN/Metal film stack. By controlling the dimensions of the periodic tuning pattern, resonance frequencies can be modulated due to mass loading effects. As a result, multiple-frequency resonators can be lithographically defined by a single deposition/patterning processing sequence. From finite element analysis, it was found that the pitch of the periodic tuning layer pattern had to be smaller than the characteristic dimension of the resonator, the membrane thickness, to avoid distortion of the resonance peak and to maintain resonator performance. This approach may lead to a viable solution for future integrated multi-mode radio RF front end.

Keywords: FBAR, resonance frequency, lithography, finite element, wireless communication

1 INTRODUCTION

Driven by fast growth of wireless communications, film bulk acoustic resonators (FBAR) have been extensively studied for RF filter applications [1]. FBAR filters have advantages of low loss, high power handling, small form factor, and easy silicon integration compared to conventional ceramic or surface acoustic wave (SAW) filters [2]. In fact, FBAR duplexers were successfully used in the front-end modules (FEM) of commercial cellular handsets. More recently, the demand for an integrated RF solution, which could include multiple bands of cellular standards, WLAN (wireless local area network), Bluetooth, GPS (global positioning system), etc., has drawn significant research efforts in providing a multifunctional, cost-effective, and low-power radio. Approaches of agile radio (or soft/software radio) and reconfigurable RF front end have been proposed and studied [3,4]. A viable solution for integrated single-chip RF front-end filters is critical to realize this version.

For RF wireless communication applications, FBARs operate in a thickness mode. The frequency of the first fundamental mode of a FBAR is determined by the thickness of the resonator's film stack, which is equal to the corresponding half-wavelength. Therefore, multiple thicknesses of film stacks are required to obtain multiple-frequency resonators/filters. However, it is not practical or manufacturable to produce multiple thicknesses by deploying sequential deposition/patterning steps. In 2004, G.Piazza et al. explored AlN piezoelectric resonators operating in contour modes with resonance frequencies determined by in-plane dimensions [5]. However, a much lower electromechanical coupling coefficient (k_t^2), 8 times smaller than that of the thickness mode, limits it in ultra-narrow bandwidth applications. In this paper, a novel approach utilizing lithographic techniques was investigated to achieve multiple resonance frequencies with high resonator performance (k_t^2 and Q) in a single chip.

2 STRUCTURE OF MODIFIED FBAR

A FBAR consists of a piezoelectric layer sandwiched between two electrodes. Two main configurations, air-gap

FBAR and solidly mounted resonator (SMR), have been used to create low acoustic impedance terminations; therefore, the acoustic energy is confined within the piezoelectric film stack, which is critical for achieving a high mechanical quality factor (Q) [6]. The air-gap FBAR has the piezoelectric film stack suspended with air on both sides. On the other hand, the SMR has an air interface on the free surface side and a quarter-wavelength acoustic mirror on the substrate side. In this paper, air-gap FBARs were used to demonstrate the integration concept, which should also be applicable to SMRs.

An additional tuning layer is added on top of the conventional FBAR film stack. Then the tuning layer is patterned as shown in the schematic (Figure 1). By controlling the width and the spacing of the tuning pattern, different mass loading (different L/S ratios) effects can be obtained. As a result, resonance frequencies of modified FBARs can be modulated by controlling the feature size of the tuning pattern.

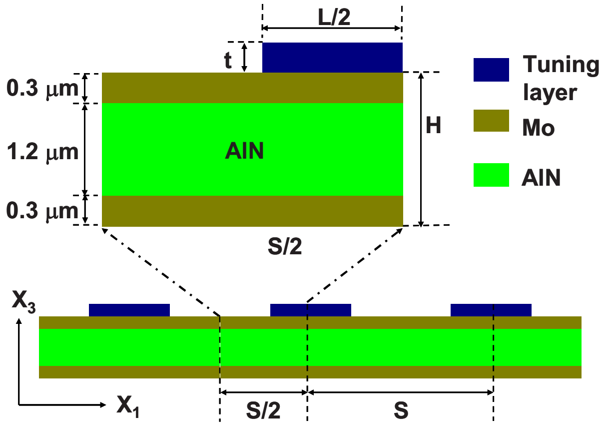

Figure 1: Schematic of a modified FBAR – a tuning layer (Mo) is added and patterned on top of a conventional FBAR

3 FINITE ELEMENT ANALYSIS

For conventional FBARs, an analytical solution can be obtained by a 1D transmission line model (TLM) [7]. However, the 1D TLM was not sufficient to analyze the modified 2D resonator. Therefore, finite element method (FEM) analysis was utilized to simulate the frequency response of modified resonators using a commercial finite element code, ABAQUS. Figure 1 shows the dimensions used in the FEM simulation. The tuning layer was patterned as periodic lines with width L and spacing S. The loading percentage is determined by the ratio of L over S. The elastic, dielectric, and piezoelectric properties of the materials are listed in Table I [8,9]. The structure was meshed by 8-node plain strain elements for Mo and piezoelectric plain strain elements for AlN. Symmetric boundary conditions were applied at the lateral boundaries of the repeated unit cell. Linear dynamics with harmonic excitation was used to analyze the steady state response at each frequency point; therefore, the frequency spectrum response was obtained by frequency sweeping analysis. The resonance frequency was determined at the maximum average strain energy.

Mo (elastic)	E=398 GPa; ν = 0.3 ρ=10200 kg/m^3
AlN (elastic)	C_{11}=396, C_{12}=137, C_{13}=108, C_{33}=373, C_{44}=116 GPa; ρ=3260 kg/m^3
Dielectric	K_{33}=9.735X10^{-11} F/m
Piezoelectric	e_{31} = -0.58, e_{33} = 1.55, e_{31}=-0.48 C/m^2

Table 1: Material properties used in FEM simulation

4 FREQUENCY RESPONSE

Effects of pattern dimensions on frequency response of the modified FBARs have to be well studied for actual implementations. Limiting cases were first studied to understand constraints. Then conditions of the desirable response (pure frequency shift) were determined.

4.1 Case I : S>>H

In this case, the pattern period (S) was much larger than the membrane thickness (H); S was 80 µm, L/S was ½, and H was 1.8 µm. The frequency response is shown in Figure 2; the strain energy shown in the y axis was normalized by the total static electrical energy in a unit cell. The result showed two distinct resonance peaks. The higher-frequency one corresponded to the thickness mode without the tuning layer and the lower-frequency one corresponded to the thickness mode with full coverage. This can also be observed from stress (σ_{33}) contour plots in Figure 2. This indicates that the modified resonator behaves like two separate resonators when the spacing was much larger than resonator's characteristic dimension, membrane thickness.

4.2 Case II: S<H

When S (=0.3μm) was smaller than H, only one single resonance peak was found (see Figure 3). The resonance peak shifted from 1.97 GHz without coverage to 1.74 GHz with 50% coverage (L/S= 0.5). The stress contour plot showed that the resonator was still in the thickness mode with mass loading from the tuning pattern. In other words, a pure mass loading effect was obtained, since the tuning pattern was small enough compared to the wavelength.

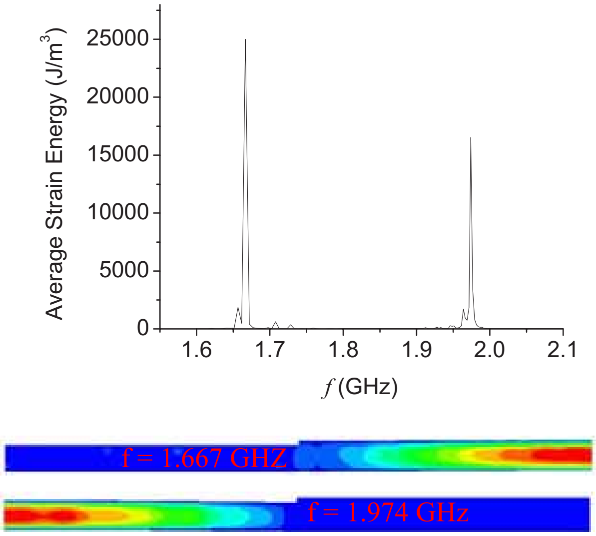

Figure 2: When S>>H, the resonator behaved like two resonators – one with full cover and one without cover.

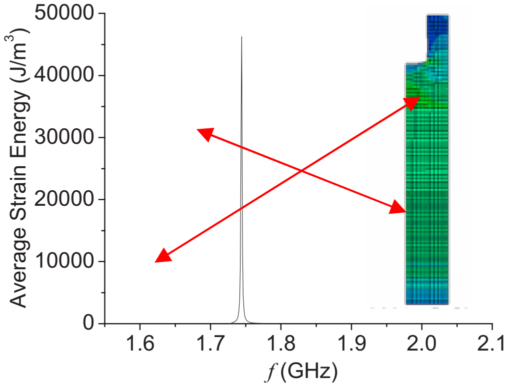

Figure 3: When S < H, a single resonance peak was observed and pure mass loading effect was valid.

4.3 Case III: S ~ H

When S (=4 μm) was comparable to or larger than H, multiple resonance peaks were found, as shown in Figure 4. The undesirable splitting of resonance peaks was due to coupling in the lateral dimensions as shown in the contour plots.

The conditions of having desirable single peak regime are summarized in Figure 5. It was concluded that S has to be smaller than 2 μm to have a single resonance peak; here, H was fixed at 1.8 μm, L/S was fixed at 0.5, and the thickness of the tuning layer (t) was 0.3 μm.

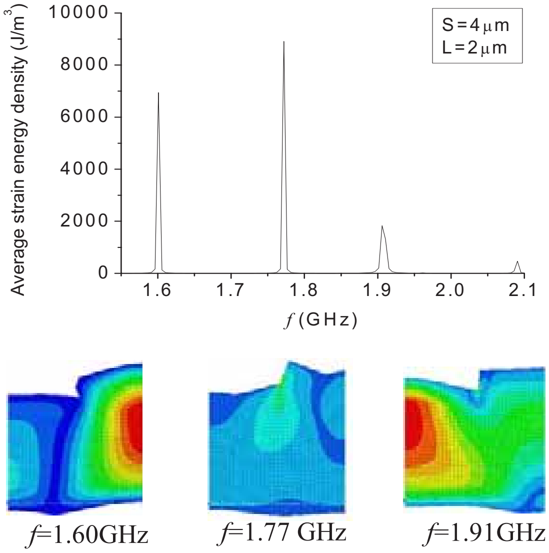

Figure 4: When S was comparable to H, multiple resonance peaks were found due to coupling in the lateral dimensions

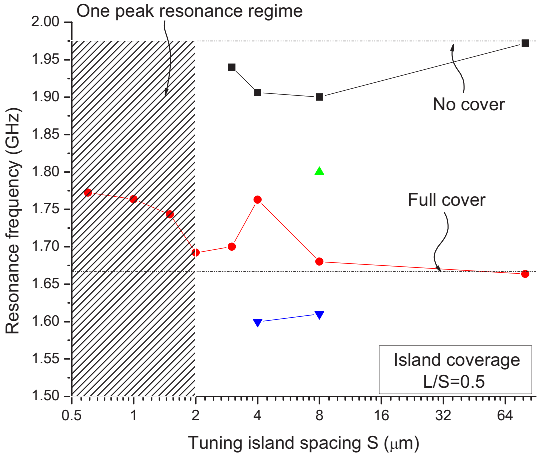

Figure 5: Single peak regime – S has to be smaller than 2 μm to have a single resonance peak.

5 MULTIPLE-FREQUENCY TUNING AND INTEGRATION

Within the single peak resonance regime (S=1.5 μm), resonance frequencies can be modulated from 1.97 to 1.67 GHz as L is changed from 0 to 1.5 μm (see Figure 6). This demonstrates that the resonance frequency can be defined by the in-plane dimension, L. Therefore, multiple-frequency resonators can be simply obtained by one lithographic processing step.

The effective electromechanical coupling coefficient (k_t^2), which is defined by equation 1, is one of the most important parameters of FBARs to be used as RF filters. Under the single peak resonance regime, Figure 7 shows that k_t^2 is maintained within 87% compared to the un-modified one.

$$k = \frac{\pi}{2}\sqrt{\frac{f_p - f_s}{f_p}} \qquad (1)$$

Where f_s is the series resonance frequency and f_p is the parallel resonance frequency.

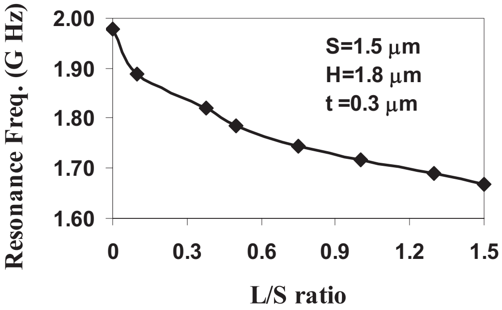

Figure 6: Resonance frequencies can be modulated by varying the pattern sizes in the single-peak regime.

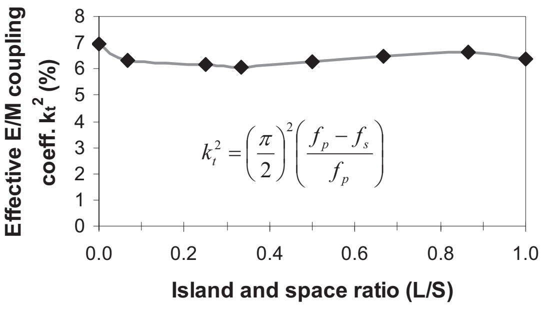

Figure 7: Effective EM coupling coefficient was maintained high at the single peak regime.

6 CONCLUSIONS

This paper has demonstrated a novel approach to integrate multiple-frequency FBARs in a single chip. It provides a unique solution to define or modify the resonance frequencies of FBARs by a lithographic patterning step. From finite element analysis, it was found that the pitch of the periodic tuning layer pattern had to be smaller than the characteristic dimension of the resonator, the membrane thickness, to avoid distortion of the resonance peak and to maintain resonator performance. This is an important development of RF filter technology for the realization of future highly integrated RF front end. Experimental explorations are being planned to investigate this approach in various nano-/micro-systems with spectrum sensing capabilities.

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