METHOD OF FABRICATING MULTIPLE-FREQUENCY FILM BULK ACOUSTIC RESONATORS IN A SINGLE CHIP

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ABSTRACT

We report experimental results of a novel approach to integrate multiple-frequency film bulk acoustic resonators (FBAR) in a single chip. An additional tuning layer was deposited and patterned on a conventional Metal/AlN/Metal FBAR film stack. By controlling in-plane dimensions of the periodic tuning patterns, resonance frequencies are modulated according to the corresponding loading percentages. To obtain a desirable frequency response of the modulated resonance peaks (a pure frequency shift), the pitch of the tuning patterns needs to be smaller than the membrane thickness. Three thicknesses of the tuning layers are fabricated to demonstrate different tuning ranges and sensitivities. This approach provides a potential solution to integrate multiple-frequency FBAR filters of adjacent bands by only one additional lithographic patterning step.

I. INTRODUCTION

An increasing demand for integrating multi-band and multi-standard RF radios, such as multiple bands of cellular standards, Bluetooth, GPS (global positioning system), WLAN (wireless local area network), etc., has drawn research efforts aimed at providing a multifunctional, cost-effective, and low-power radio. Approaches of agile radio (or soft/software radio) and a reconfigurable RF front end have been proposed and studied [1,2]. For the reconfigurable RF front end, integration of adjacent-band filters in one chip is attractive from cost and simplicity perspectives.

Film bulk acoustic resonator (FBAR) filters have proven advantages of low loss, high power handling, small form factor, and easy silicon integration compared to conventional ceramic and surface acoustic wave (SAW) filters [3,4]. The resonance frequency of a FBAR is determined by the thickness of the film stack, which is equal to the corresponding half-wavelength of the first fundamental mode [5]. However, it is impractical from a manufacturing perspective to have multiple thicknesses of film stacks in order to obtain multiple-frequency resonators/filters. In 2004, Piazza *et al*. explored AlN piezoelectric resonators operating in contour modes with resonance frequencies determined by in-plane dimensions [6]. A much lower electromechanical coupling coefficient (k_e^2), which is a key parameter for the use of FBARs as a front-end RF filter, was obtained.

This paper describes an approach for integrating multiple-frequency FBARs in a single chip. A theoretical study has been previously reported [7]. This work addresses the fabrication and testing of the modified FBARs for experimental validation of the novel concept.

II. INTEGRATION APPROACH

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). 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 work, only air-gap FBARs were used to demonstrate the concept, which should also be applicable to SMR FBARs.

The key concept of the frequency tuning is based on the mass loading effect. An additional tuning layer was added on top of the conventional FBAR membrane, Mo/AlN/Mo film stack. Then the tuning layer was patterned with a pitch of S and width of L. A schematic of the modified FBAR is shown in Figure 1. Therefore, different mass loading (different L/S ratios) effects can be obtained by controlling the width and the pitch of the tuning patterns.

III. FABRICATUION

The fabrication process is shown in Figure 2. The substrates were 6-in diameter (100) silicon wafers. It started

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with a silicon trench etch, followed by trench fill using silicon dioxide as a sacrificial layer. The surface was planarized by a chemical-mechanical-polishing (CMP) step. It is important to have a very smooth surface for the following piezoelectric film stack deposition. A bottom Mo layer (0.32µm) was sputtered and patterned to define the electrode area. The AlN layer (1.1µm) was deposited by reactive sputtering. This was followed by top Mo electrode and tuning layer (Mo or AlN) deposition. The trimming and top Mo layers were patterned using different photomasks to define loading patterns and top electrode area, respectively. The AlN layer was dry etched to open contact windows on bottom Mo electrodes and form release holes. Finally, the sacrificial layer was etched with BOE to release the membrane. Figure 3 shows optical and SEM micrographs of a modified FBAR after completion of the fabrication.

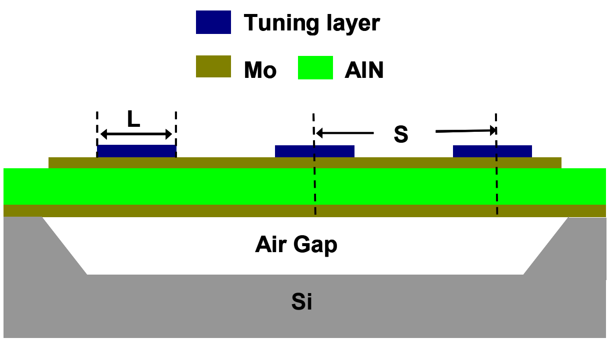

Figure 1. Schematic of a modified FBAR – a tuning layer (Mo) is added and patterned on top of a conventional FBAR

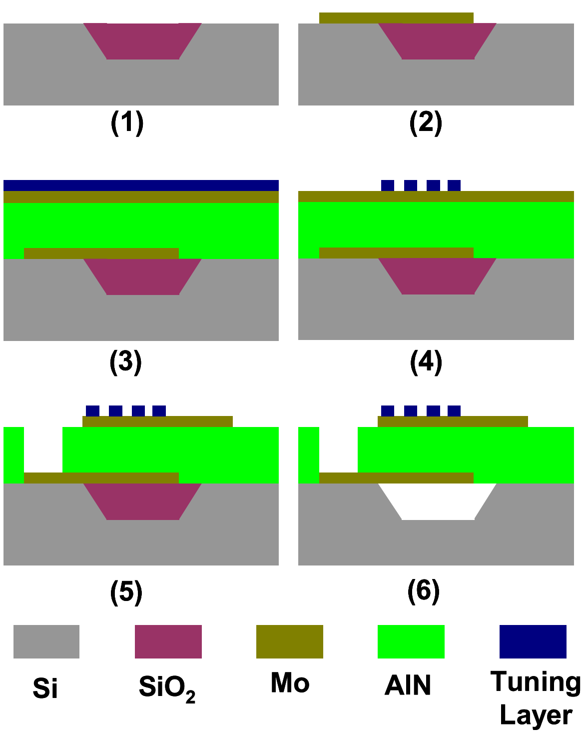

Fig. 2. Process flow of fabricating modified FBARs based on surface-micromachining technique

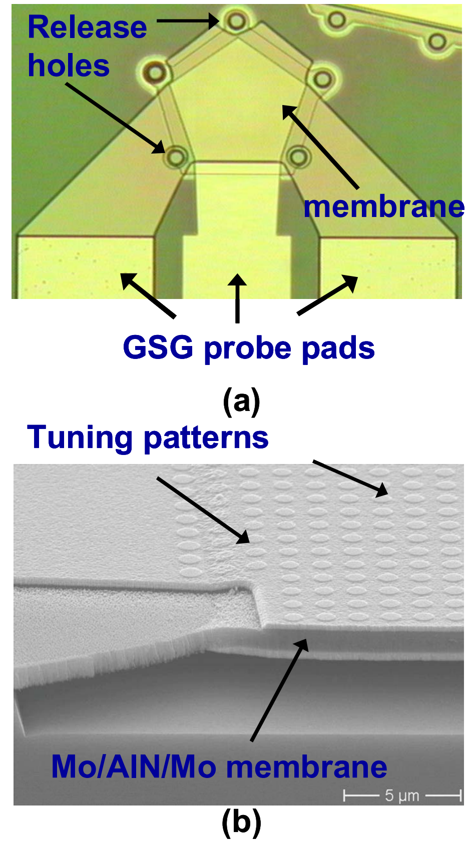

Fig. 3. (a) Optical photograph of a FBAR with GSG probe pads for RF testing; (b) SEM micrograph of a released FBAR membrane, showing a Mo tuning layer that was deposited and patterned on top of the membrane.

IV. Results and Discussion

The FBARs were RF tested using an Agilent network analyzer. One-port S-parameters were measured to obtain the input impedance of the resonators. Series resonance frequency (f_s) and parallel resonant frequency (f_p) can be obtained. The k_e^2 was calculated using equation (1). Comparison of different loading FBARs was made on the same die to minimize the frequency variation caused by the thickness variation of the deposited films (typically <0.2% within die variation).

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

When the pitch of tuning patterns (40 µm) was much larger than the membrane thickness (1.8 µm), two distinct resonant peaks were measured and shown in Figure 4. The lower-frequency peak corresponded to the thickness mode with the tuning pattern and the higher-frequency one corresponded to the thickness mode without the tuning layer. The two resonant peaks agreed with the prediction from the finite element analysis (FEA), where stress-contour plots show two distinct resonant modes at the corresponding frequencies as shown in Figure 4.

To achieve a desirable frequency response, the tuning patterns with 1.5 μm pitch and five different loading percentages, 0, 20, 42, 64, and 100%, were designed and fabricated. The tested results, shown in Figure 5, demonstrate that the resonant frequencies were modulated in relation to the corresponding loading percentages. More importantly, the modulated resonance peaks maintain the same shape as the non-modulated one; that is, a pure frequency shift was achieved.

Three different thicknesses of tuning layers (75, 100, and 150nm Mo) were fabricated to study total tuning ranges and sensitivities. The results illustrated in Figure 6a clearly demonstrate that the thicker tuning layer provides, as expected, a larger loading effect and a wider total tuning range. For all modified FBARs, the effective coupling coefficient, k_e^2, was maintained within 90% of the non-modified one (see Figure 6b).

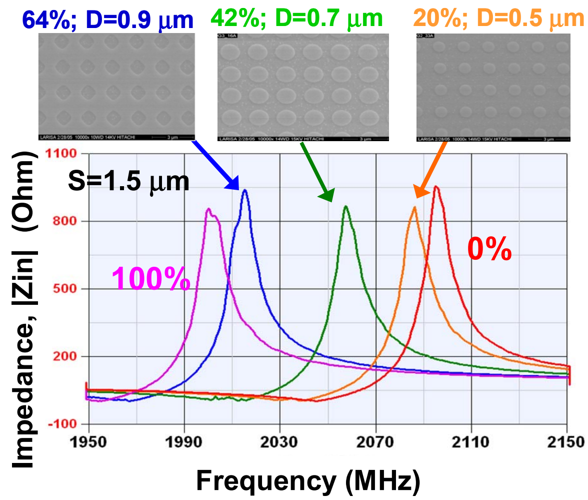

Figure 5. Resonance frequencies were modulated according to the loading percentages. The resonant peaks of modified FBARs maintain a desirable response, a pure frequency shift, when the pitch (S=1.5μm) is smaller than the membrane thickness (1.8μm).

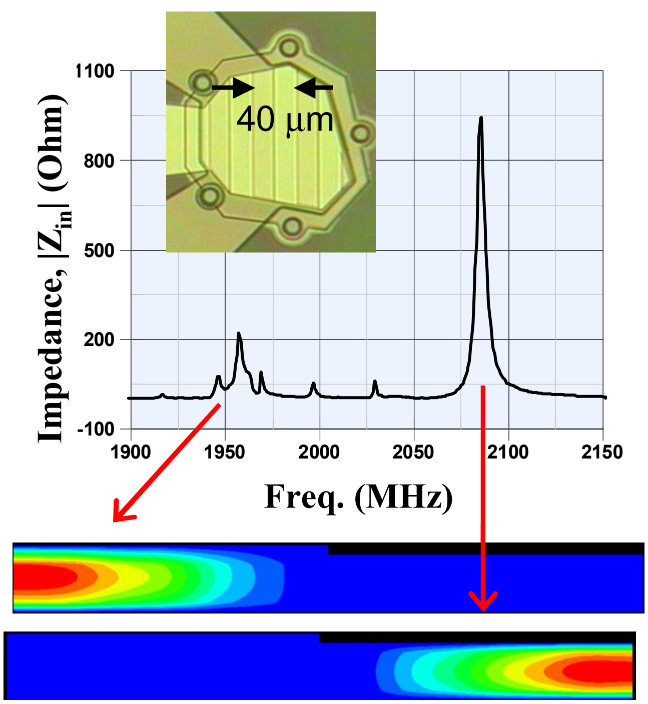

Figure 4. When the pitch of tuning patterns (40 μm) was much larger than the membrane thickness (1.8 μm), two distinct resonant peaks were found from the measured result and agreed with FEA simulation.

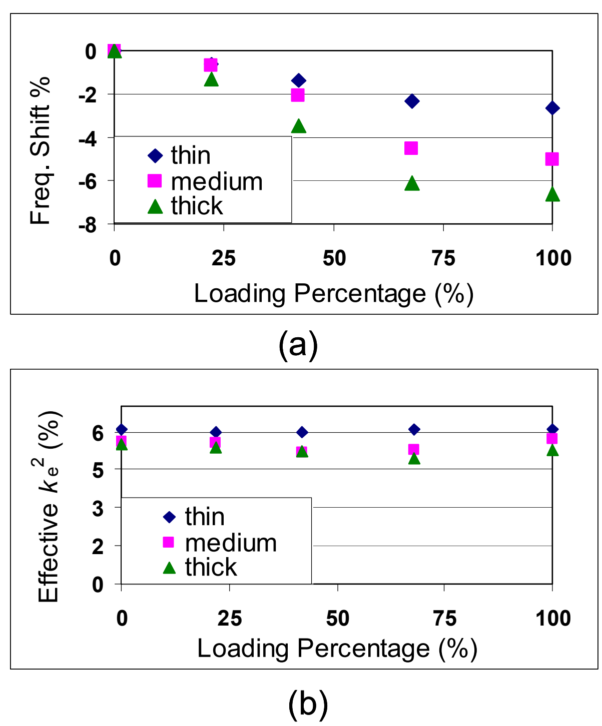

Figure 6. (a) Three different thicknesses of tuning layers were tested at five loading conditions. The thicker tuning layer provided a larger loading effect (steeper slope) and a wider total tuning range. (b) The effective coupling coefficient (k_e^2) of all modified FBARs was maintained within 90% of the non-modified one.

V. CONCLUSIONS

We demonstrate a unique approach to integrating multiple-frequency FBARs in a single chip. By controlling in-plane dimensions of the periodic tuning patterns, resonance frequencies of modified FBARs are modulated corresponding to the mass loading percentages. As a result, multiple-frequency FBARs can be lithographically defined by a single deposition/patterning processing sequence. To obtain a desirable frequency response, a pure frequency shift, the pitch of the tuning patterns needs to be smaller than the membrane thickness. This approach provides a potential solution for integrating multiple-frequency FBAR filters of adjacent bands or frequency trimming.

ACKNOWLEDGMENT

The authors would like to thank Advanced Modular Sputtering, Inc. (AMS) and Trikon Technologies, Inc. for helping on piezoelectric films.

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