AlN BAW-like Resonators with Patterned Top Electrodes Achieving Coupling Coefficient up to 8% at >2.5GHz

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Abstract— This paper reports the design concept and the implementation of a new class of aluminium nitride (AlN) thin film resonators, whose resonant frequencies are above 2.5GHz, achieving k^2_{eff} as high as 8%, high than that of bulk acoustic wave (BAW) resonators. The functional layer of the resonator is formed by a 1µm-thick AlN film sandwiched between top and bottom molybdenum (Mo) layers with the thicknesses of 0.26µm and 0.2µm, respectively. The bottom electrode is of a plate structure, in order to ensure subsequent high-quality AlN growth by avoiding fine-pattern electrodes underneath AlN; while the top electrode is design to be one array of electrically connected comb fingers, allowing the design freedom to adjust the resonator frequency by lithographically patterning of the top electrode layer. Great potential is demonstrated by this new class of resonators in achieving ultra wideband filter for 5G application.

Keywords—AlN, coupling coefficient, high frequency, resonator

I. INTRODUCTION

With mobile communication evolves in 5G era, the demand of radio frequency (RF) front-end band selection filter increases drastically due to the increased number of frequency bands as well as the massive adoption of Multiple-Input Multiple-Output (MIMO) and carrier aggregation (CA). The general trend of the filter requirement is wider bandwidth at higher center frequency. From the aspect of technology category, surface acoustic wave (SAW) filter is adopting multi-layer structure called I.H.P SAW [1-3] or guided SAW to improve the quality factor and bandwidth at operating frequency above 2GHz. While for bulk acoustic wave (BAW) filter, the main technique of increasing bandwidth is through material innovation by doping AlN with scandium (ScAlN), however at the price of slight degradation of the quality factor.

Other than commercially available SAW and BAW filters, researchers have attempted to use AlN thin film, but different acoustic wave modes such as contour mode [4-8] to overcome the limitation of BAW technology which is the frequency is infirst-principle determined only by film stack. However, there's no successful demonstration of such resonators with effective coupling coefficient (k^2_{eff}) which is the main parameter determining the achievable filter bandwidth exceeding that of BAW ($k^2_{eff} \sim 7\%$). The highest k^2_{eff} achieved by non-BAW AlN resonators are laterally coupled alternating thickness (LCAT)

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Figure 1. Schematic of the resonator proposed. Top electrode pitch (p) and the electrical connection scheme are also illustrated.

mode resonator with k_{eff}^2 of 6.3% [9]. One major challenge of implementing LCAT mode resonator with high quality factor is on how to grow high quality AlN on electrodes with fine pattern. To address this concern, the modified version of LCAT mode resonator with unpatterned bottom electrode was designed and fabricated[10, 11], but the achieved k_{eff}^2 is further degraded as compared with inter-digitated (IDT) bottom electrode.

This paper presents the first design and experimental results of a series of AlN thin-film resonator achieving k^2_{eff} higher than BAW resonator, while allowing the design freedom of adjusting the resonator frequency by lithographically patterning of the top electrode layer.

II. DEVICE DESCRIPTION

The functional layer of the resonator is formed by a 1µmthick AlN film sandwiched between top and bottom molybdenum (Mo) layers with the thicknesses of 0.26µm and 0.2µm, respectively. The top electrode of the resonator is formed by comb fingers and the bottom electrode is a plate, as illustrated in Fig. 1. Unlike lamb wave resonators or LCAT mode resonators whose adjacent electrode fingers are excited by electrical signals with opposite polarity, all top electrodes of the resonator in this work are electrically shorted by a bus bar, also shown in Fig. 1. Similar to BAW resonators, AC voltage is applied across the top and bottom electrode of the resonator during operation.



Fig. 2 (a) Simulated frequency response for resonators with comb electrode pitch (*p*) varying from 0.5µm to 1.4µm. (b) Series resonant frequency (f_s) and the derived k^2_{eff} of the resonators with *p* varying from 0.5µm to 1.4µm. (c) The resonant mode shape of the resonator with p = 0.5µm.

The definition of electrode pitch (p) is also illustrated in Fig. 1. Unlike BAW resonators whose performance is dominated by bulk acoustic mode, the resonator in this work consists of both vertical and lateral acoustic modes, since the top electrode is finger patterned. The resonant frequency also partially depends on the top electrode pitch. To quantify the performance of the resonator, 2-dimentional (2D) finite electrode analysis (FEA) using ANSYS is performed to obtain the frequency response and the mode shape of resonators with p varying from 0.5µm to 1.4µm and finger width is p/2 for every device. Resonator's k^2_{eff} is calculated using equation (1), where f_s is the series resonant frequency, and f_p is the parallel resonant frequency.

$$k_{eff}^{2} = \frac{\pi}{2} \frac{f_{s}}{f_{p}} \frac{1}{\tan\left(\frac{\pi}{2} \frac{f_{s}}{f_{p}}\right)}$$
(1)



Fig. 3 (a) The top view of one fabricated resonator. (b) Measured frequency response for resonators with *p* varying from 0.5 μ m to 1.4 μ m. (c) *f_s* and the k^2_{eff} , which is derived from measurement results, of the resonators with *p* varying from 0.5 μ m to 1.4 μ m.

The simulated impedance of the resonators with p varying from 0.5µm to 1.4µm versus frequency is plotted in Fig. 2(a), while their f_s and the derived k^2_{eff} are shown in Fig. 2(b). With the increase of p, f_s decreases together with k^2_{eff} . Observing from the mechanical mode shape of the resonator with p = 0.5µm as shown in Fig. 2(c), the displacement profile is quite similar to that of BAW, in which the elements in the upper part of the resonator moves up, while the lower part of the resonator moves in the opposite direction. The difference is that the amplitude of the displacement is higher at positions under the top fingers. Although the amplitude of the bottom electrode displacement also varies periodically, the wavelength is much larger than the top electrode pitch.

III. EXPERIMENTAL RESULTS

The resonators are fabricated using our in-house 8-inch facilities. The 8-mask process is described in [11]. The microscopic image of the top view of one resonator is shown in Fig. 3(a).

S-parameters of the resonators are measured using a 2-port network analyzer and then converted to the resonator's impedance. As depicted in Fig. 3(b) which shows the measured frequency response for resonators with *p* varying from 0.5µm to 1.4µm, and Fig. 3(c) which shows their f_s and the derived k^2_{eff} , with the increase of top electrode finger pitch from 0.5µm to 1.4µm, the f_s reduces from around 2.7GHz to 2.5GHz, and k^2_{eff} drops from ~8% to ~5%. The BAW resonator fabricated on the same wafer has f_s at 2.48GHz and k^2_{eff} of 7.1%. To the authors' knowledge, this is the first experimental results demonstration k^2_{eff} of AlN resonator beyond that of BAW.

The successful demonstration of this new class of resonators with k^2_{eff} higher than BAW resonator moves AlN family MEMS technology a significant step closer towards achieving ultra wideband filter for 5G application.

IV. CONCLUSIONS

This paper presents the design concept and the implementation of a new class of AlN thin film resonator achieving k_{eff}^2 as high as 8% at above 2.5GHz, avoiding fine-pattern electrodes underneath AlN, and yet allowing the design freedom to adjust the resonator frequency by lithographically patterning of the top electrode layer.

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