UNPRECEDENTED FIGURE OF MERIT IN EXCESS OF 108 IN 920 MHz ALUMINUM NITRIDE CROSS-SECTIONAL LAMÉ MODE RESONATORS SHOWING k_t^2 IN EXCESS OF 6.2%

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ABSTRACT

In this work we demonstrate a 900 MHz cross-sectional Lamé-mode resonator showing a k_t^2 in excess of 6.2% and a loaded quality factor in excess of 1750. Such a high k_t^2, which closely matches that Finite-Element-Methods (FEM) predicted value, is attained through the use of a 3-finger CLMR and a thickness-field-excitation (TFE) scheme. This device not only shows a high k_t^2 comparable to the one attained by film-bulk-acoustic resonators, FBARs, but is also characterized by an unprecedented figure-of-merit (FoM∽108) that, to the best of the authors' knowledge, is the highest demonstrated in AlN resonators operating at ~1 GHz.

INTRODUCTION

Micro Electro Mechanical (MEM) resonators are key enablers for the development of miniaturized and low-power multi-band radio-frequency (RF) systems capable of operating in the extremely crowded modern commercial and military spectral environment.

For years, MEM resonators have been researched for their ability to attain high quality factors (Q) and large electromechanical coupling coefficients (k_t^2) in small volumes. Recently, the complete maturation of the Aluminum Nitride (AlN) Film-Bulk-Acoustic resonator (FBAR) technology [1] has allowed the replacement of off-chip surface acoustic wave (SAW) devices in commercial products, hence enabling better performance in a miniaturized form-factor.

The AlN FBAR technology relies mainly on the e_{33} piezoelectric coefficient of AlN to transduce resonant vibration along the thickness of an AlN plate. As the device resonance frequency (f_r) is set by the thickness of the AlN plate (T_{AlN}), it cannot be tuned lithographically. As a consequence, the integration of multi-frequency FBAR-based filters on the same chip can only be attained through an increase of the fabrication complexity (i.e. by mass-loading or trimming). Such a limitation has been overcome by the AlN contour-mode resonator (CMR) technology [2]. In fact, AlN CMRs rely mainly on the e_{31} piezoelectric coefficient of AlN to transduce resonant vibration along an in-plane direction of an AlN plate (e.g., width extensional or length extensional motion). Therefore, the lithographically set lateral dimension of the device determines its resonance frequency, enabling the fabrication of CMRs operating in the Ultra-High- (UHF), Very-High- (VHF) and Super-High- (SHF) frequency ranges on the same chip [3],[4]. Although multi-frequency AlN CMRs can be readily integrated on the same chip, their k_t^2 is lower than that of FBARs, due to the intrinsically lower amplitude of the e_{31} compared to the e_{33}. For this reason FBAR-based filters have been preferred to the CMR-based ones for the implementation of low insertion loss and wideband passive filtering networks.

More recently, AlN cross-sectional Lamé-mode resonators were demonstrated (CLMRs) [5],[6]. CLMRs are piezoelectric resonators formed by two metallic IDTs sandwiching an AlN plate. They rely on the combined use of both the e_{31} and the e_{33} piezoelectric coefficients of AlN to transduce a Lamé-mode in the cross-section of an AlN plate through. Thanks to this special feature, CLMRs can simultaneously achieve high-k_t^2 and a lithographic definition of their resonance frequency (f_{res}), enabling the implementation of lithographically defined integrated contiguous and not-contiguous pre-select filters for platforms adopting carrier-aggregation (CA).

In this work we demonstrate 1-port CLMRs simultaneously showing a record-high k_t^2 in excess of 6.2%, a quality factor (Q) in excess of 1750 and a Figure of Merit (*i.e.* FoM=$Q \cdot k_t^2$) in excess of 108. To the best of the authors' knowledge, such a high FoM-value is the highest ever demonstrated in AlN resonators operating in the same frequency range.

CROSS-SECTIONAL LAMÉ MODE RESONATORS

AlN CLMRs are piezoelectric resonators capable of transducing a Lamé-mode in the cross-section of AlN plates through the coherent combination of the e_{31} and e_{33} piezoelectric coefficients of AlN (Fig. 1). Thanks to the opposite sign of these two piezoelectric coefficients, in-phase charge components are generated by vibration along both the cross-sectional directions (thickness and width) of the plate. As a consequence, the k_t^2 attained by AlN CLMRs is function of both the e_{31} and e_{33} piezoelectric coefficients of AlN, and it is higher than the k_t^2 achieved by conventional laterally vibrating AlN resonators such as CMRs.

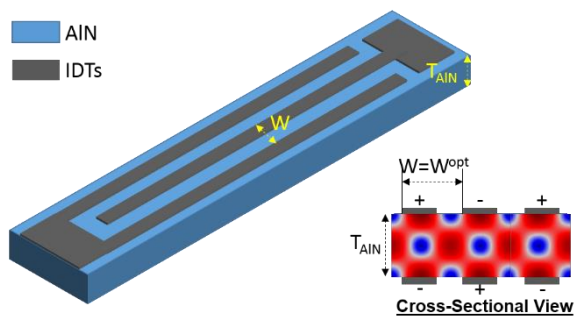

Figure 1: schematic-view of a 3-finger CLMR. The device is formed by two IDTs sandwiching an AlN film. The pitch of the IDTs (W) is selected to be similar to the thickness of the AlN layer (T_{AlN}). Such choice enables the excitation of high-k_t^2 degenerate or nondegenerate Lamé-modes in plates. The mode-shape relative to the total displacement of the same device, when exciting a nondegenerate Lamé mode, is also reported.

Similarly to CMRs, CLMRs can be excited through either a Lateral-Field-Excitation (LFE) [7] or a thickness-field-excitation (TFE) approach [6]. LFE CLMRs are formed by one set of IDT patterned on either the top or the bottom surface of an AlN layer. In contrast, TFE CLMRs are formed by two interdigital-metal electrodes sandwiching an AlN film. The IDTs, in both TFE and LFE CLMRs, are needed to produce the excitation of the electric field in the cross-section of the AlN layer.

As demonstrated in [5], CLMRs achieve maximum k_t^2-value when the pitch of the IDTs (W) is set to a specific value (W^{opt}) similar to thickness (T_{AlN}) of the AlN plate. In fact, in this scenario, a nondegenerate Lamé-mode is excited in the cross-section of the AlN plate. However, due to the capability of exciting

high-k_t^2 *degenerate* cross-sectional Lamé modes [8] in plates, CLMRs can attain high k_t^2 also when W is slightly different from W^{opt}. In addition, since f_{res} depends on W, the transduction of such degenerate modes also enables a significant lithographic tunability of the device operating frequency. This feature is crucial for the implementation of multi-frequency resonators and filters monolithically integrated on the same chip with minimal fabrication complexity. In this work, a non-degenerate CLMR (adopting the optimum IDT geometry, *i.e.* $W=W^{opt}$) showing a record k_t^2 in excess of 6.2% is experimentally demonstrated for the first time.

Fabrication Process

The CLMRs presented in this work are formed by a 4 µm thick AlN layer and two 0.1 µm thick platinum IDTs placed on the top and bottom surfaces of the AlN film. The choice of using platinum for the bottom IDT was dictated by the need of growing a high quality AlN film. Platinum was also used for the top IDT in order to preserve high acoustic symmetry in the device cross-section.

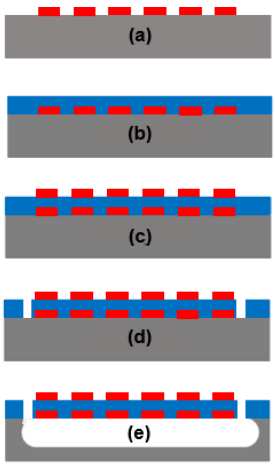

Figure 2: Microfabrication process of TFE CLMRs: (a) Pt film was deposited on top of Silicon, through a 10 nm thick Ti layer used as adhesion layer, and patterned through lift-off process; (b) AlN film was deposited on top of the Pt film and vias in the AlN were formed; (c) Pt film was deposited on top of Si and patterned through lift-off process; (d) AlN film was etched through the use of a SiO_2 hard mask that was preferred to traditional photoresist mask to attain steeper AlN sidewalls; (e) Si substrate was released by XeF_2 isotropic etching.

The devices were fabricated using a four-mask micro-fabrication process (Figure 2): 10/100 nm of Ti/Pt was deposited and patterned on top of a high resistivity silicon wafer to form the bottom IDT. Next, a 4 µm thick AlN film was sputter-deposited. Then, we etched AlN through wet etching to form the vias. Next, 10/100 nm of Ti/Pt was deposited and patterned to form the top IDT. Then, the AlN film was etched by ICP in Cl_2 based chemistry to define the width of the AlN plate. This was done through the use of a hard mask made out of 2 µm of SiO_2 so as to attain steep AlN sidewall angles (>75°). Finally, the Silicon substrate underneath the resonator was released through XeF_2 isotropic etching.

High-FoM exceeding 108 in AlN CLMRs

3-fingers 920 MHz TFE CLMRs were fabricated. These devices are formed by two 100-nm thick platinum IDTs sandwiching a 4-µm thick AlN-plate. The pitch of their IDTs was optimized (*i.e.* W was set to 5 µm), through simulation, in order to maximize the simulated k_t^2 value. A Scanned Electron Microscope (SEM) picture of one of the fabricated CLMRs is shown in Figure 3.

Two quarter-wave acoustic transformers were designed at the edges of the device [9] in order to minimize the loss of acoustic energy through the anchors (*i.e.* known as anchor-losses) [10],[11]. As verified through 3D-FEA (Figure 4), this technique, which was originally developed for AlN CMRs, is also effective in minimizing the displacement in the inactive-regions of CLMRs, thus enabling a reduction of anchor-losses and, consequently, a larger mechanical quality factor (Q_m). Both the 3D-FEA simulated and measured admittance (Y) curves relative to the best fabricated CLMRs (Figure 3) are reported in Figure 5.

As evident, a k_t^2 value in excess of 6.2% was extracted through MBVD-fitting [12] of the measured response. Such value matches closely the predicted value (~6.6%) found through FEA, thus confirming its validity. In addition, the measured response showed a loaded quality-factor, Q_{load}, (extracted from the measured device 3dB- bandwidth), in excess of 1750. Such high Q_{load} and k_t^2 values allowed to achieve a measured FoM in excess of 108. To the best of the authors' knowledge, such a large FoM is the highest ever demonstrated in AlN resonators operating in the same frequency range.

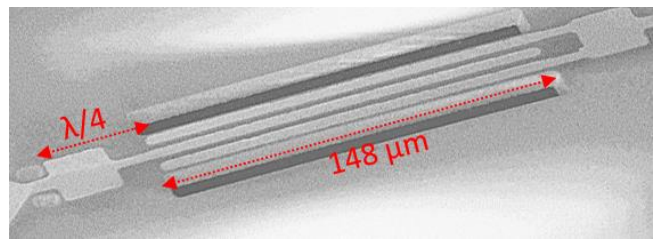

Figure 3: Scanned-Electron-Microscope picture of a fabricated CLMR.

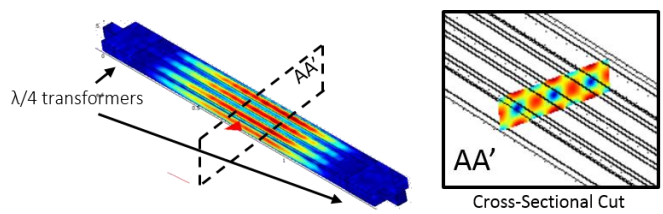

Figure 4: left) Simulated modal-distribution of the device displacement, through 3D-FEA. As evident, the use of the acoustic quarter-wave transformers enables a significant reduction of the magnitude of the total-displacement reaching the resonator inactive-regions; right) 3D-FEA simulated cross-sectional modal distribution along a cut-plane (AA') at the resonator center. As evident this modal-distribution matches closely what found with the 2D-FEA analysis reported in Figure 1.

In addition, several spurious-modes, which could not be found through 2D-FEA (Figure 5), were instead detected in both the measured and the 3D-simulated admittance responses (Y). Although their origin is still under investigation, these spurious modes are likely due to the transduction of low-coupling transverse modes propagating along the resonator length, hence not being detectable through 2D-FEA. Strategies to suppress such undesired modes of vibration remain under investigations.

CONCLUSION

This paper reports on crucial advances in the development of monolithic integrated RF-passive components based on the recently developed Aluminum Nitride (AlN) cross-sectional Lamé-mode (CLM) piezoelectric technology. In particular, we

demonstrated a cross-sectional Lamé-mode resonator (CLMR) operating around 920 MHz and showing k_t^2 and Figure-Of-Merit (FoM) in excess of 6.2% and 108, respectively.

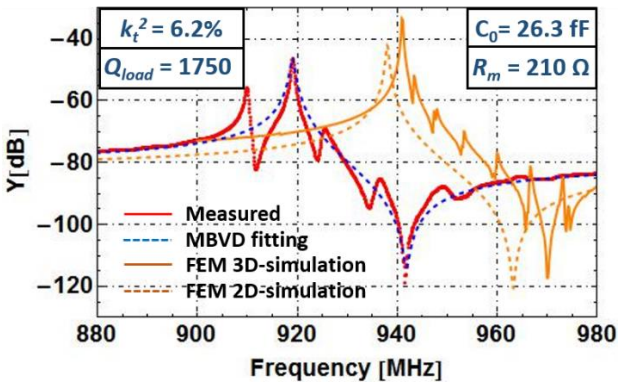

Figure 5: red) Measured admittance response of the best fabricated CLMR. The device was tested, in air, by probing it through Ground-Signal-Ground (GSG) probes. The device response was de-embedded from 10 fF of parasitic capacitance associated with the probing pads; blue) MBVD-model fitting of the measured admittance. The device static capacitance (C_0), motional resistance (R_m), quality factor (Q_{loaded}) and k_t^2 are extracted from the MBVD-model fitting [13]. *Orange) 2D-FEA (dashed-line) and 3D-FEA (continuous-line) simulated admittances of the best fabricated CLMR.*

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