Aluminum Nitride Cross-Sectional Lamé Mode Resonators with 260 MHz Lithographic Tuning Capability and High $k_t^2 > 4\%$

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***Abstract*—We experimentally demonstrate Aluminum Nitride (AlN) cross-sectional Lamé mode resonators (CLMRs) operating in the microwave frequency range and showing high $Q \cdot k_t^2$ products (*FoM*) in excess of 85. Such feature enables low motional resistance (R_m) values (37 Ω) in CLMRs characterized by low static capacitance (C_0) approaching 66 fF. In addition, the ability of CLMRs to simultaneously achieve high k_t^2 (> 4%) and a lithographic frequency tunability (> 260 MHz around 900 MHz) is experimentally demonstrated, for the first time, in this work. Such important feature renders CLMRs promising candidates to replace off-chip Surface Acoustic Wave (SAW) devices in lithographically defined filters for next-generation wireless communication platforms.**

Keywords*—*Acoustic resonators, filters, electromechanical coupling coefficient, Aluminum Nitride.

I. INTRODUCTION

The steadily growing need of service bands in wireless communication platforms has increased the demand of miniaturized and high-performance low-power radio-frequency (RF) filters. Aluminum Nitride (AlN) resonators are promising candidates to replace off-chip Surface Acoustic Wave (SAW) devices in RF front-ends. In particular, thanks to their high-performance and small form-factor, filters based on AlN film-bulk-acoustic resonators (FBARs) have already replaced many SAW-based filters in commercial handsets [1]. However, as the resonance frequency of FBARs is set by their thickness, multi-frequency FBAR-based filters can be built on the same chip only through more elaborate fabrication processes. AlN contour-mode resonators (CMRs) appeared as promising candidates as AlN CMRs possess the ability of frequency tuning by lithography. However, the electromechanical-coupling coefficient (k_t^2) of AlN CMRs is limited by the relatively weak piezoelectric coupling of the contour-extensional mode in AlN [2]. Only recently, AlN cross-sectional Lamé mode resonators have been demonstrated [3], [4]. Such devices can achieve similar k_t^2 than FBARs, thus enabling comparable fractional-bandwidth (BW) than FBAR-based filters. However, as experimentally demonstrated in this work, the resonance frequency (f_r) of CLMRs depends on the pitch of the metallic interdigitated transducers (IDTs) used to actuate and sense the mechanical vibration in AlN plates. Consequently, CLMR-based filters operating at different center-frequencies can be monolithically integrated on the same chip without adding fabrication complexity and, consequently, rise the manufacturing cost. In this work, the electromechanical performance of CLMRs is investigated. In particular, the variation of electromechanical-coupling coefficient (k_t^2), resonance frequency (f_r) and resistance at resonance frequency (R_{fr}) (i.e. the sum of series resistance R_s and motional resistance R_m), with respect to the pitch of the IDTs (W) are investigated in CLMRs made out of 4 μm of AlN. Our experiments demonstrate that CLMRs can achieve high-k_t^2 (> 4%) in a large lithographically defined bandwidth (260 MHz around 900 MHz).

Furthermore, we demonstrate a high $Q \cdot k_t^2$ product (figure of merit, FoM) in excess of 85 in a CLMR (Figure 1) characterized by low static-capacitance ($C_0 \backsim$ 66 fF). Such high value of FoM is to the authors' knowledge the highest ever reported in AlN resonators using IDTs.

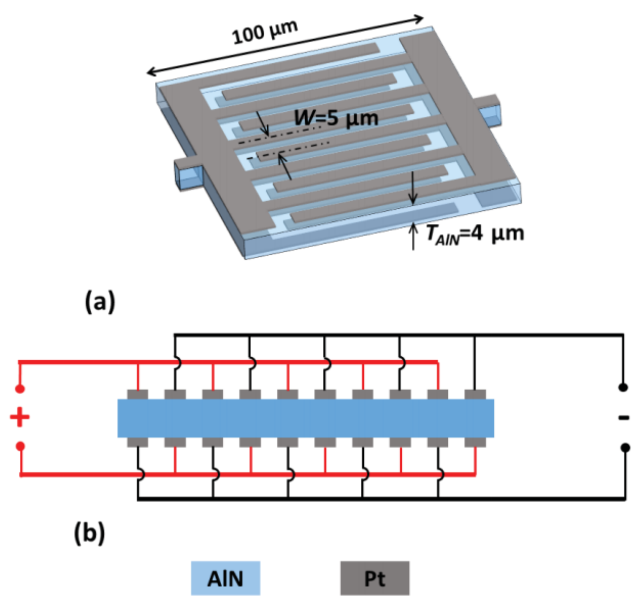

Figure 1: (a) 3D schematic representation, (b) cross-sectional view of CLMRs.

II. EXPERIMENTAL RESULTS

The devices were built using a 4-mask fabrication process, as shown in Figure 2. A 100 nm thick platinum (Pt) layer was firstly deposited and patterned by liftoff on a high resistivity silicon (Si) wafer to define the bottom IDT. A 4 µm thick AlN was then sputter-deposited and wet etched to form the vias. After that, a 100 nm Pt was again deposited and patterned for the top electrode. The shape of the resonant plate was defined by dry etch with a hard mask made of 2 µm SiO_2. Finally, the devices were structurally released by XeF_2 isotropic etching of Si. Quarter-wave ($\lambda/4$) transformers were integrated between the edge of the active region and each adjacent anchor for all the devices in order to minimize the anchor dissipations [5]. The length of the CLMRs was designed to be 100 µm, and the overall width was set by the pitch, *W*, and the number of finger (Figure 3).

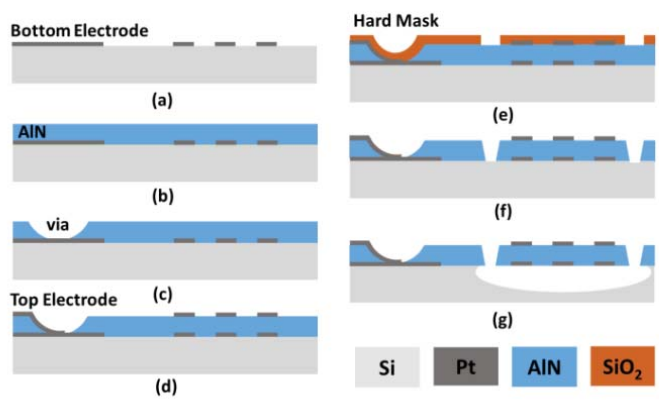

Figure 2: Microfabrication process: (a) sputter deposition and liftoff of Pt bottom electrodes; (b) deposition of 4 µm AlN; (c) wet etch of AlN for vias; (d) sputter deposition and liftoff of Pt top electrodes; (e) deposition and etch of 2 µm SiO_2 as hard-mask; (f) dry etch of AlN; (g) XeF_2 dry release.

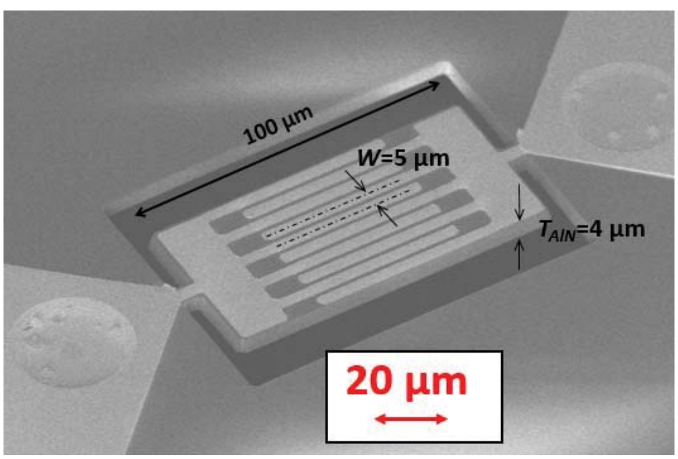

Figure 3. Scanning electron microscope (SEM) image of a 10-finger CLMR fabricated in this work.

The experiments were carried out based on 18 fabricated resonators with 5 different pitches (W = 3, 4, 5, 6, and 7 µm). The dependences of k_t^2 and f_r on the pitch size (W) of the IDTs were investigated. The measured average k_t^2 values, and simulated k_t^2 values (by 3D finite element analysis using CoventorWare) for each pitch size are reported in Figure 4. Evidently, the measured average k_t^2 reached its peak when the pitch size was selected to be around 5 to 6 µm. And an almost identical trend can be found in the simulation results. Such optimized pitch enables the excitation of a non-degenerate cross-sectional Lamé mode in a 4 µm thick AlN plate sandwiched between two 100 nm thick platinum IDTs.

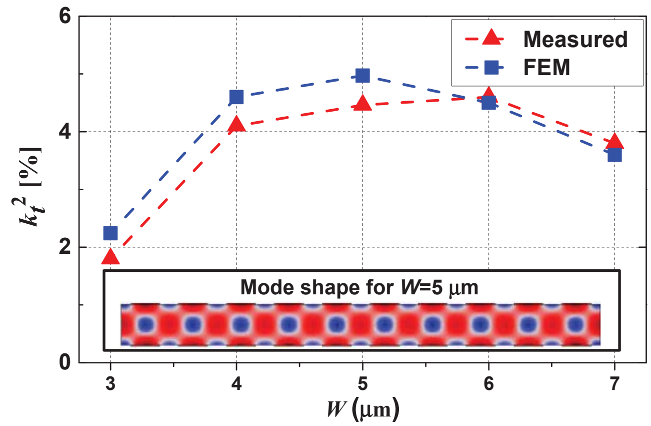

Figure 4: (a) Measured (in red) and 3D simulated (in blue) k_t^2 as a function of the pitch of the IDTs used to actuate and sense the mechanical motion in CLMRs. All tested devices have a 60% metal coverage independently on W. The FEM simulated mode-shape relative to the total displacement of the fabricated CLMRs is also reported; as evident, a high k_t^2 value in excess of 4% can be achieved by selecting W to be included between 4 and 6.5 µm.

The measured resonance frequencies and k_t^2 values for each pitch, W, are reported in Figure 5, showing that CLMRs can achieve high-k_t^2 (> 4%) in a large lithographically defined bandwidth (> 260 MHz around 900 MHz). Such lithographic tuning capability is sufficient to form filters for next-generation mobile platforms adopting carrier-aggregation and permits to build both transmit and receive filters on the same chip without complicating the fabrication process [6].

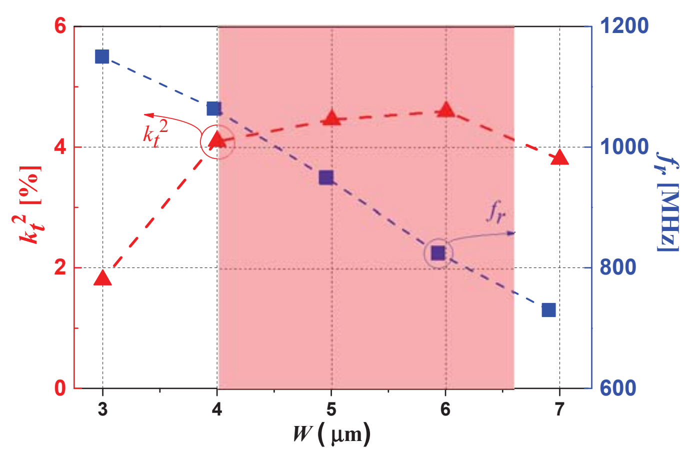

Figure 5: (a) Measured k_t^2 (in red) and resonance frequencies (in blue) as a function of pitch, W. All tested devices have a 60% metal coverage independently on W. The shadowed area highlights the pitch sizes and corresponding frequency range (from ~ 770 MHz to ~ 1.03 GHz) where CLMRs can be lithographically tuned while preserving high k_t^2 > 4%.

The highest loaded quality factor, Q_{load}, measured for each pitch size and the corresponding total resistance at resonance frequency, R_{fr} ($R_s + R_m$), extracted from modified Butterworth-Van Dyke (MBVD) model fitting are reported in Figure 6, showing a low impedance of CLMRs for potential direct integration with 50 Ω electronics.

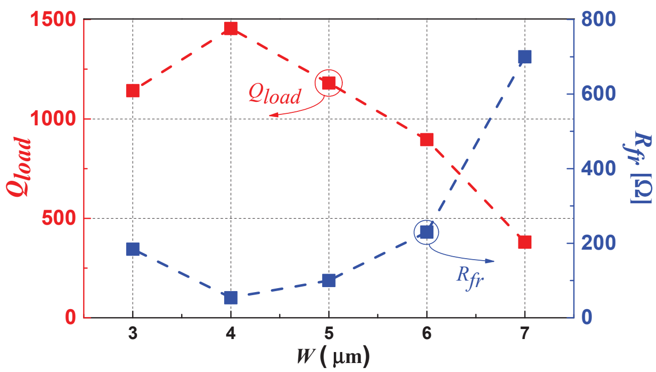

Figure 6: Measured R_{fr} (in blue) and Q_{load} (in red) as a function of pitch when metal coverage is set to 60% of the pitch. Lowest R_{fr} and high Q_{load} present for pitches of 4 μm.

Furthermore, the measured, simulated and fitted (through MBVD fitting) admittance curves of the best fabricated CLMR are shown in Figure 7. A Q_{load} in air of 1635 and a k_t^2 of 4.3% were recorded, thus resulting into a FoM close to 85. Such value is, to the best of our knowledge, the highest ever reported in AlN resonators using IDTs to actuate and sense the mechanical vibration in the AlN plate. The measured response was de-embedded from parasitic capacitance and series resistance due to the probing-pads. As evident both the measured and the simulated responses are affected by a spurious-mode (at 950 MHz in measurement) close to the device parallel resonance frequency. This mode, which is a higher-order Lamb-wave mode, can be suppressed in the future through the strategic optimization of the geometry of the IDTs.

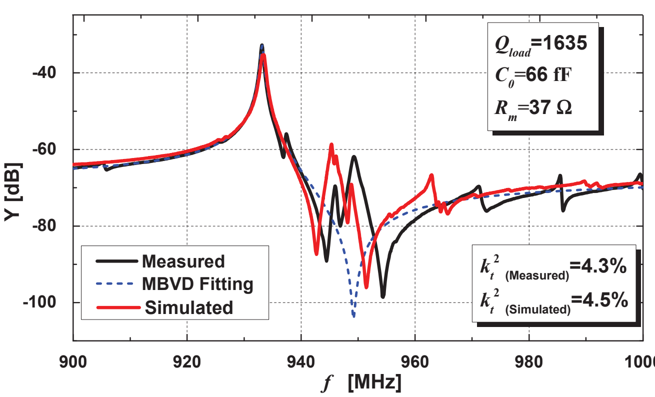

Figure 7: Measured (in black), fitted (in blue) and simulated (in red) responses of the best CLMR recorded in this work. An 80 MHz resonance frequency shift observed between measurement and simulation results is believed to be caused by inaccurate definition of material parameters and device dimensions.

III. Conclusion

In this paper, aluminum nitride (AlN) cross-sectional Lamé mode resonators (CLMRs) operating in the microwave frequency range were designed, fabricated and characterized, showing a record high $Q{\cdot}kt_2$ products in excess of 85. In addition, for the first time, the ability of CLMRs to simultaneously achieve high electromechanical-coupling (k_t^2 > 4%) and a lithographic tuning capability of frequency (> 260 MHz around 900 MHz) was experimentally demonstrated. Such achievements of CLMRs set a stepping stone towards the development of next generation monolithically integrated mobile platforms featuring wide spectrum coverage and low loss.

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