A Manufacturable AlScN Periodically Polarized Piezoelectric Film Bulk Acoustic Wave Resonator (AlScN P3F BAW) Operating in Overtone Mode at X and Ku Band

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***Abstract*—This paper reports a manufacturable, Periodically Polarized Piezoelectric Film (P3F) Bulk Acoustic Wave (BAW) resonator using Aluminum Scandium Nitride (AlScN) materials operating in overtone mode at X and Ku band. P3F BAW technology benefits from a significantly larger film thickness than the traditional BAW thickness-frequency scaling approach, enabling a manufacturable, high quality-factor (Q), and high frequency resonator technology. A P3F material stack was realized using a combination of single and polycrystalline AlScN layers with desired polarity of layers as deposited, which enables volume manufacturing. An AlScN P3F BAW resonator was manufactured using XBAW®, a unique and patented transferred substrate process technology for next generation resonator and filter solutions. The fabricated P3F BAW resonators demonstrated 2nd overtone operation at 10.7 GHz & 18 GHz, and exhibits a FoM, (Qp × kt2) of 27 and 20, respectively. This result suggests that AlScN P3F BAW using overtone mode operation enables miniature, manufacturable, BAW RF filter technology for X band and higher frequencies.**

***Keywords*— P3F, AlScN, BAW, XBAW, Resonators, RF Filters, MEMS, X-band, mm-wave, acoustic filters**

I. Introduction

Current implementations of next generation wireless standards, such as 5G and Wi Fi 6E/7 utilize available spectrum within 2 to 7 GHz and offer 160/320 MHz wide channels enabling high-capacity and high data rate communication systems. These high-performance wireless RF communication systems seek to optimally use the available frequency spectrum and channel bandwidths and are enabled by high-performance bulk acoustic wave (BAW) vibration modes [1 3], and surface acoustic waves [4-5]

BAW filters utilize Aluminum Scandium Nitride (AlScN) piezoelectric films because Sc concentration in AlScN films is an engineering knob to create resonators with higher coupling coefficients [6] which enables higher bandwidth required for these high-performance filters. BAW resonators are attractive for their high quality-factor (Q) which enables lower passband loss and steeper filter skirts. High coupling and high Q combine to make AlScN BAW technology attractive for miniature, low-loss, high-rejection, high-bandwidth RF filters with good shape factor, as required for next generation wireless systems.

The need for ever increasing data rates and channel capacity has been addressed by the 3GPP standards organization by defining two frequency ranges for 5G wireless systems i.e., FR1, utilizing the sub-7 GHz frequencies and FR2, which includes frequencies in the millimeter wave (mm wave) from 24 to 100 GHz and specifically in the 24 to 40 GHz range [7]. In addition to 5G commercial bands, IEEE defines frequency bands X through Ka, for radar applications, corresponding to spectrum ranging from 8 to 40 GHz [8]. It is evident from these standards and definitions that there exists a requirement for compact, high performance filter solutions in the 8 to 40 GHz spectrum.

We previously presented [13-14] the capability of XBAW®, a unique transferred substrate manufacturing process that can utilize either physical vapor deposition (PVD) or metal organic chemical vapor deposition (MOCVD) AlScN material with high Sc concentrations, to create high FoM (Qp × kt2) resonators, at frequencies within 2 to 7 GHz. In this work, we present an AlScN P3F BAW technology, fabricated using XBAW® and using overtone mode operation, which can enable miniature, manufacturable, acoustic RF filter technology for X band and higher frequencies.

II. Motivation

As described earlier, BAW and related piezoelectric resonators have been commercialized for filtering solutions below 7 GHz. For frequencies higher than approximately 7 GHz, filtering solutions tend to use electromagnetic (EM) wave resonances implemented using waveguides and cavities to create filter responses. [9-10]. However, because filter size is directly related to wavelength and propagation velocity, EM filters are significantly larger than acoustic wave devices. Size and footprint constraints are major limiting factors in the number of filtering elements that a wireless system solution can implement. Besides larger size, when compared to BAW filters, EM filters can have lower Q, leading to larger insertion loss and worse shape factors.

Therefore, there exists a need for miniature, high Q filtering solutions in the 8 to 40 GHz spectrum using non EM approaches, such as acoustic, piezoelectric resonators which can enable desired system attributes such as filtering at individual elements in RF Front Ends (RFFE) [11-12].

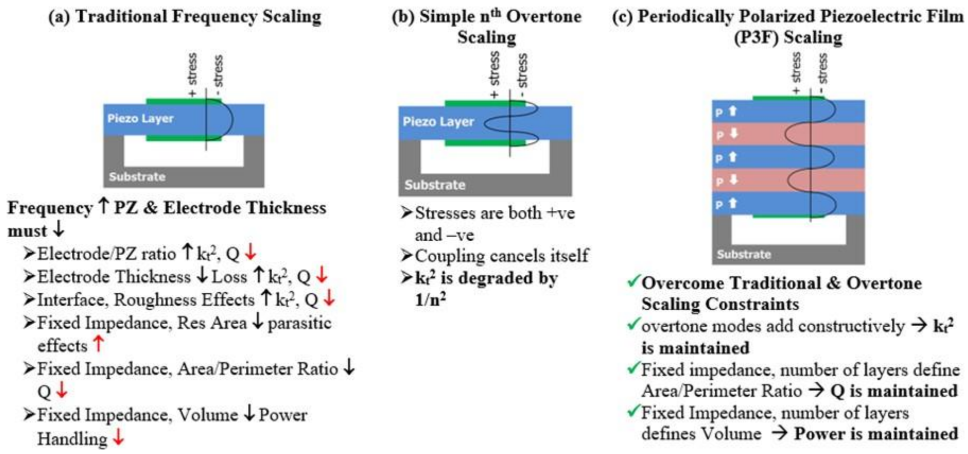

Fig 1. Comparison of different approaches to BAW scaling for higher frequency, showing benefits of P3F scaling.

III. P3F Scaling For Higher Frequency

It is well understood [3], [15-17] that the traditional thickness frequency scaling approach for BAW resonators (which utilize the thickness extensional (TE1) "breathing" vibration mode), has several disadvantages for frequencies above 8 GHz, primarily because piezoelectric film thicknesses reduce below the 200 nm range.

These disadvantages are summarized in Fig 1(a). The decrease in film thickness implies a decrease in resonator area for a fixed impedance, resulting in a decrease in the area/periphery ratio, for any resonator shape. These factors lower efficacy of acoustic energy confinement, reducing acoustic Q. Additionally, as explained in [15], electrode/piezoelectric thickness ratios are constrained to obtain desired coupling, leading to a trade between filter bandwidth and filter loss. An alternative approach to mitigate effects of resistive loss at mm-wave frequencies has been recently reported [18]. A simple overtone scaling approach, as shown in Fig 1(b), mitigates thickness reduction but degrades coupling by the square of the overtone mode, as is well understood [19]. So, a different approach to utilizing overtone modes is required.

The use of oppositely polarized layers to simultaneously increase the total piezoelectric thickness and avoid any decrease in electromechanical coupling has been reported by several researchers [20-22]. Several methods have been described to realize such oppositely polarized piezoelectric layer stacks, including doping [23], seed layer [24-25], heat treatment [20], bonding [19] and electrical poling [22]. Independent of the specific method of realizing such oppositely polarized layers, the frequency scaling benefits of such a P3F layer stack are well known [19], [21-22], as explained in Fig 1(c).

Although the method of creating a P3F layer stack does not impact the theoretical benefits to P3F frequency scaling, it is noted that a manufacturable and scalable P3F technology ideally requires – (1) a manufacturable method of creating a P3F starting wafer, (2) no additional complex steps within the device fabrication flow after the starting P3F wafer begins device fabrication, and (3) the P3F layer stack does not further constrain the realization of filter circuits, i.e., additionally constrain circuit interconnections and external connections to the filter die. In this work, we present such a manufacturable and scalable P3F resonator and filter technology.

IV. Fabricated AlScN P3F BAW Resonator

Control and P3F layer stacks were fabricated using the same XBAW process. As shown in Fig 2(a), both control and P3F have the same total piezoelectric thickness (460 nm) but the P3F stack uses two 230 nm thick AlScN layers of opposite polarization. As shown in Fig 2(b, c), integrated differential phase contrast scanning transmission electron microscopy (iDPC-STEM) images of the P3F stack clearly show a layer of N-polar AlScN on a layer of M-polar AlScN.

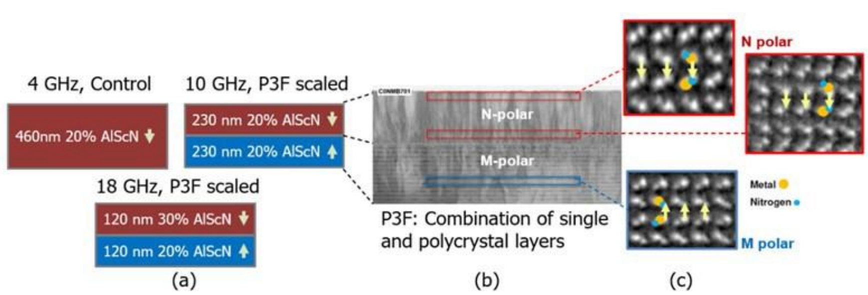

Fig. 2 (a) P3F stack, (b) TEM image of P3F realization, (c) TEM results showing desired polarity.

As seen, N-polar AlScN has consistent polarity throughout the film thickness. The P3F stack was realized by a combination of single and polycrystalline AlScN layers with the desired polarity in each layer, as deposited. Standard XBAW devices were fabricated, as shown in Fig 3.

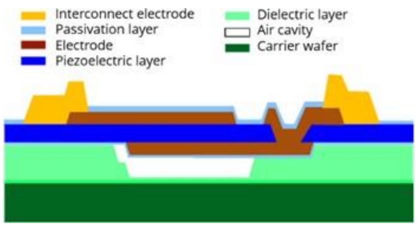

Fig 3. XBAW Process and Device Technology structure.

A P3F BAW stack was designed using Mason's model and as expected from P3F scaling, the measured resonance frequency is 10.7 GHz, as seen in Fig 4. Both baseline and P3F stacks were processed in the XBAW® process, which allows growth of thin films on a flat seed substrate in a manner that is not possible with conventional BAW resonator manufacturing procedures. This XBAW® process is versatile such that high-performance resonators can be produced from a wide variety of piezoelectric films including sputtered polycrystalline AlN to single crystal, high Sc content AlScN films [6, 26].

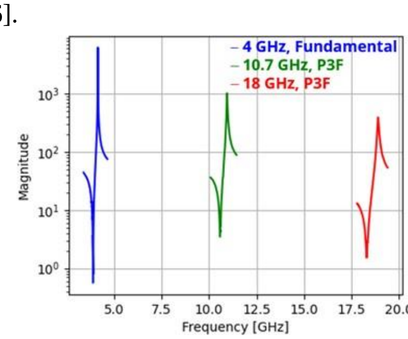

Fig. 4. Impedance response of control and P3F scaled resonator.

The fabricated resonators were tested using an on-wafer, 1-port configuration with an air coplanar ground-signal probe. The measured performance of the AlScN resonators reported in this work are summarized and compared with reported resonators in Table 1, providing context to the data reported here. The electromechanical coupling, and acoustic FoM in this table was calculated using the equation below.

$$k_t^2 = \frac{\pi}{2}\frac{f_s}{f_p}\cot\left(\frac{\pi}{2}\frac{f_s}{f_p}\right);\ FoM\ I = k_t^2 Q_p. \qquad (1)$$

The 50 Ω XBAW device using the single layer $Al_{0.8}Sc_{0.2}N$ layer was designed for 4 GHz and exhibited k_t^2 of 13.8%. Q_s, and Q_p are 1279 and 909, respectively, which translates to a figure-of-merit (FoM I), product of Q_p and k_t^2, of 125. The 50 Ω XBAW device using the P3F stack of $Al_{0.8}Sc_{0.2}N$ was designed for 10.7 GHz and exhibited k_t^2 of 7.94% and a Q_s, and Q_p of 150 and 342, respectively which translates to a FoM I of 27.2. Another figure of merit, $FoM\ II = f_p \times FoM\ I$, listed in Table I, accounts for the frequency dependence of Q.

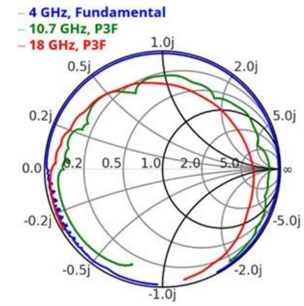

Fig. 5. Smith chart of control and P3F scaled resonators.

To show that AlScN P3F BAW capability extends to Ku and potentially higher frequency bands, another resonator was designed for 18GHz operation. Measured resonator performance at 18.4GHz is shown in Fig 4 and Fig 5 and key metrics summarized in Table 1. A Smith chart overlay of all measured devices in Fig 5 shows, not unexpectedly, that the P3F device exhibits undesired vibration modes in addition to the desired main TE_2 mode. Appropriate engineering of the device structure is expected to mitigate and/or eliminate these undesired modes.

V. Conclusion

In this work, the authors report a manufacturable Periodically Polarized Piezoelectric Film (P3F) Bulk Acoustic Wave (BAW) resonator using Aluminum Scandium Nitride (AlScN) materials and operating in a 2nd overtone mode at 10.7 GHz. P3F BAW technology benefits from a significantly larger film thickness than traditional thickness frequency scaling approaches for high frequency, enabling a manufacturable, high Q, high-frequency resonator technology. This AlScN P3F BAW resonator was manufactured using XBAW®, a patented and manufacturable transferred substrate process technology for next generation resonator and filter solutions. A P3F material stack was realized using a combination of single and polycrystalline AlScN layers with the desired polarity of the layers achieved as deposited, which enables volume manufacturing. P3F BAW resonators were fabricated demonstrating 2nd overtone operation at 10.7 GHz and 18.4GHz and exhibiting a FoM (Qp × kt2) of 27 and 20, respectively. This result suggests that AlScN P3F BAW using overtone mode operation enables miniature, manufacturable, high Q, BAW RF filter technology for X and Ku band and higher frequencies.

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Table 1. Resonator performance summary and comparison with published work.

Material	Freq. Scaling Approach	f_s (GHz)	f_p (GHz)	k_t^2	Q_s	Q_p	FoM I $k_t^2 \times Q_p$	FoM II $k_t^2 \times Q_p \times f_p$	*Source*
32 % Sc-doped AlN	Traditional	3.61	3.94	19.00%	776	574	109	429	*[14]*
32 % Sc-doped AlN	Traditional	4.8	5.23	18.70%	545	630	118	617	
28 % Sc-doped AlN	No poling	7.04	7.32	10.10%	-	115	12	85	*[22]*
28 % Sc-doped AlN	Periodically Polarized (Electrically Poled)	13.4	13.97	10.70%	-	151	16	226	*[22]*
AlN	Overtone	33.4	33.9	1.70%	110	85	1.4	49	*[18]*
LiNbO3	Periodically Polarized (Bonded)	9.05	9.9	3.71%	-	636	24	234	*[19]*
20 % Sc-doped AlN	Traditional	4	4.25	13.80%	1271	909	125	533	*This work*
20 % Sc-doped AlN on 20% Sc-doped AlN	Periodically Polarized (As-Grown)	10.68	11.05	7.94%	150	342	27	300	
30% Sc-doped AlN on 20% Sc-doped AlN	Periodically Polarized (As-Grown)	18.4	19	7.55%	180	260	20	373	

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