An mm-Wave Trilayer AlN/ScAlN/AlN Higher Order Mode FBAR

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Abstract— **Modern wireless communication systems are increasingly complex with greater functionality and impose new challenges on the radio frequency (RF) front-end design. One of the major challenges involves filtering beyond the sub-6-GHz regime with increased fractional bandwidth (FBW). To the best of our knowledge, this work presents the first demonstration of a film bulk acoustic wave resonator (FBAR) with a composite ferroelectric/piezoelectric transduction layer (consisting of AlN–Sc$_{0.3}$Al$_{0.7}$N–AlN) that is capable of selectively operating at higher order resonant modes without compromising k_t^2 for applications in the millimeter wave (mm-Wave) spectrum. The resonator exhibits a fundamental mode at GHz with k_t^2 of 5.2% but can switch to a higher order response at 31 GHz by reversing the polarization direction in the ScAlN layer (k_t^2 of 5.5%).**

Index Terms— **Aluminum nitride (AlN), electromechanical coupling coefficient (k_t^2), microwave acoustics, scandium aluminum nitride (Sc$_x$Al$_{(1-x)}$N), thin film bulk acoustic wave resonators (FBAR).**

I. INTRODUCTION

PIEZOELECTRIC-BASED resonators have been the predominant technology of choice for radio frequency (RF) filtering in mobile devices, owing to a number of distinct advantages compared with other technologies. This includes their miniature size and highly efficient electromechanical transduction mechanism, which determine the overall quality factor (Q) and fractional bandwidth (FBW) of the filter. Piezoelectric materials, such as aluminum nitride (AlN) and zinc oxide (ZnO), have proven commercial success, but only up to an RF spectrum of 6 GHz. Attempts to scale these acoustic wave devices higher in frequencies lead to a number of issues in regard to device performance.

For bulk acoustic wave (BAW) resonators and filters, which are capable of higher power handling and frequency, higher frequency operations lead to a reduction in the piezoelectric layer thickness [1]. While commercially fabricated AlN-based

resonators, operating in the thickness-extensional mode, are capable of providing electromechanical coupling between 5% and 6% with high-quality factors in the sub-6-GHz regime, new approaches in microwave acoustics are required to not only scale the operating frequency range into millimeter wave (mm-Wave) frequencies but also meet FBW requirements [2].

A number of studies on novel materials, such as lithium niobate (LiNbO$_3$), and resonators have been proposed for scaling the frequency range [3], but one approach that has attracted interest employs scandium-doped AlN (ScAlN) in order to increase the d$_{33}$ coefficient in AlN by a factor of four, thereby increasing k_t^2 [4], [5]. Already, there have been a number of reported ScAlN-based acoustic wave resonators [6], [7]. Moreover, as a ferroelectric, ScAlN provides a method for realizing reconfigurable filters through tuning and polarization switching properties. As an alternative approach, multilayer ferroelectric-based resonators provide a method to selectively excite different harmonic modes without compromising k_t^2 [9]. Higher order, multilayer resonators based on ferroelectrics, such as barium strontium titanate and more recently, ScAlN, have been demonstrated by applying electric field bias to control the sign of the piezoelectric coefficients [6], [9]. However, these proposed devices still encounter key challenges: 1) maintaining Q and k_t^2 across multiple growths of thin film ferroelectric materials on electrodes and 2) lithography patterning for access to bias intermediate electrodes along with associated parasitics. The work conducted in this letter is the first demonstration of a trilayer AlN–ScAlN–AlN-based resonator that eliminates the need for intermediate electrodes in such multilayer resonator designs and resonates at different modes based on selectively controlling the polarization direction of ScAlN film through electric field bias. The demonstrated trilayer ScAlN resonator has fabrication requirements that are compatible to currently employed commercial BAW device technologies. The organization of the letter is as follows: design and simulation for the resonator are discussed in Section III. The later sections present measurements of the trilayer resonator after polarization switching.

II. FBAR DESIGN AND FABRICATION

A. Principle and Design

The ScAlN film bulk acoustic wave resonator (FBAR) described in this work operates with three transduction layers (AlN–Sc$_{0.3}$Al$_{0.7}$N–AlN) placed between two electrodes. This allows for control over the sign of piezoelectricity in
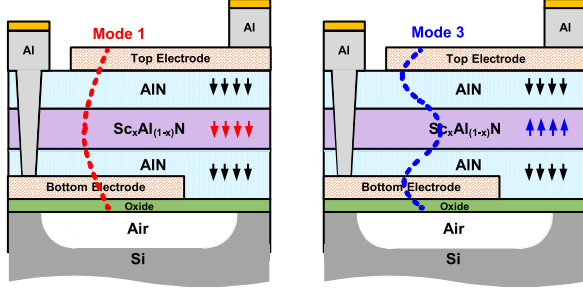
Fig. 1.   Structure of the trilayer ferroelectric ScAlN FBAR in fundamental mode and higher order mode.

TABLE I
TRILAYER FBAR PHYSICAL PARAMETERS

Layer	Value
d_{AlN1}	95 nm
$d_{Sc0.3Al0.7N}$	85 nm
d_{AlN2}	120 nm

the middle ferroelectric layer. Through the application of low-frequency electric field bias on the electrodes, the ScAlN layer can switch polarization direction, selectively operating at different resonant modes, as shown in Fig. 1. It should be noted that while operating in the higher order mode of the resonator, the fundamental mode is also suppressed because the piezoelectric coefficient is orthogonal to the strain profile of the mode [9].

The resonators are designed using a 1-D Mason model [10] with a thin Sc_2O_3 layer underneath the bottom Mo electrode, where the first piezoelectric AlN layer and substrate thickness are designed for a half acoustic wavelength. The subsequent ScAlN and AlN layers thicknesses are set to ensure zero strain locations occur at the material interfaces. The material parameters for the ScAlN and AlN layers in the Mason model are derived from [11] to [12] along with prior film measurements, and Table I lists the thicknesses of the resonator layers. Fig. 2 shows the simulated response of the trilayer resonator for the two polarization directions of the ScAlN film.

B. Fabrication Process

The fabrication process for the ScAlN/AlN FBAR is shown in Fig. 3, starting with Mo/Sc_2O_3 layers on high resistivity Si substrate. The bottom Mo layer is patterned using dry etching before the piezoelectric–ferroelectric–piezoelectric layers are molecular beam epitaxially (MBE) grown in a Veeco Genxplor MBE system, where the grown $Sc_xAl_{(1-x)}N$ film had a composition ratio of $x = 0.3$. Following growth, the ScAlN and AlN layers are etched using a combination of timed ion milling and wet etching with AZ 726 developer solution in order to create the GND vias. Subsequently, a thin layer of the electrode is deposited and patterned by evaporation and lift-off. An additional ion milling is then conducted to etch through the Sc_2O_3 layers to create the release windows. All masking for the ion milling and wet etches use an SPR 220 (3.0) photoresist. Then, a contact layer of Ti/Al/Ti/Au (20/600/5/100 nm) is patterned using evaporation and lift-off
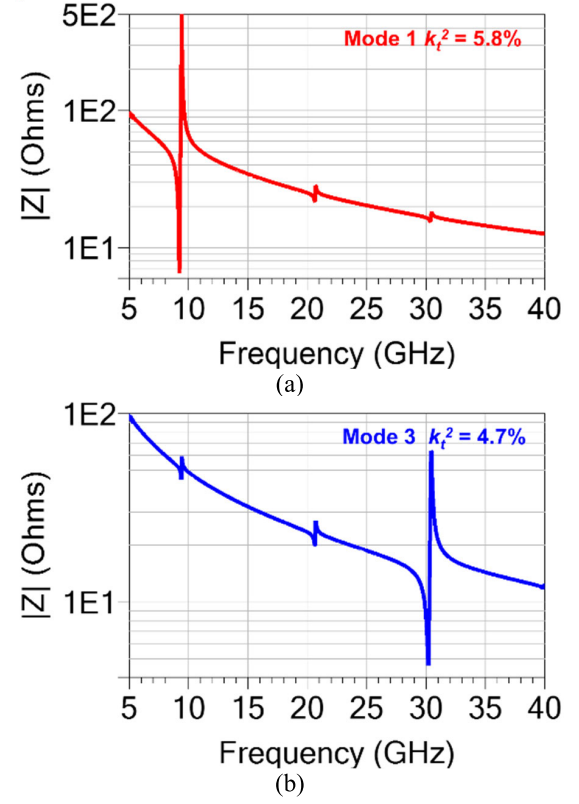

Fig. 2.   Simulated impedance response of the trilayer ScAlN FBAR in both (a) initial state and (b) reversed polarization state.
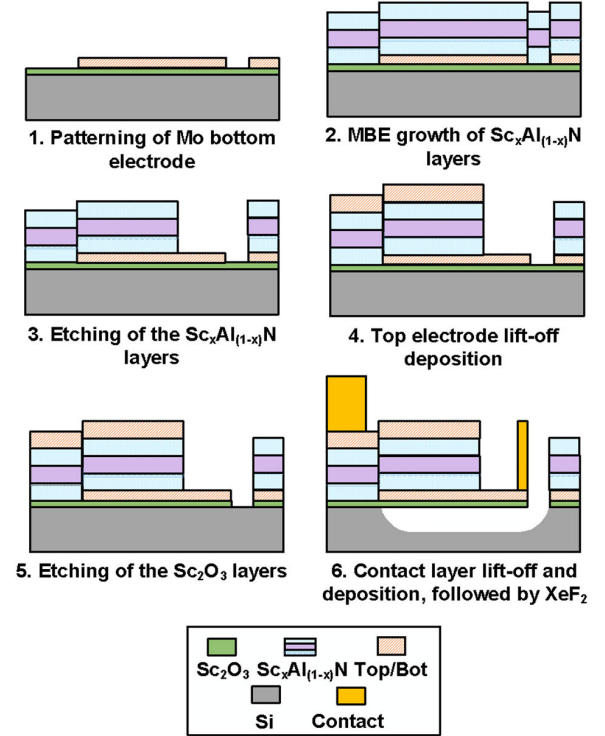

Fig. 3.   Fabrication process for the trilayer ScAlN FBAR.

before the devices are fully released by etching the Si substrate in a 3.0 torr XeF2 environment.
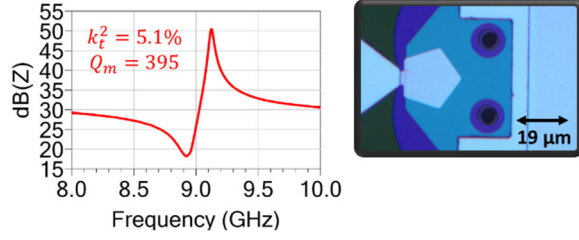
Fig. 4. Measured impedance response of mode 1 for the trilayer ScAlN FBAR in the initial state and photograph of the fabricated resonator.

TABLE II
mBVD MODEL PARAMETERS—MODE 1

Parameter	Value	Parameter	Value
L_m (nH)	27.66	C_e (pF)	0.28
R_m (Ω)	3.96	R_e (Ω)	1.32
C_m (pF)	0.01	R_s (Ω)	2.85

III. POLING AND MEASUREMENT RESULTS

The fabricated ScAlN FBAR is measured using a PNA E8364C network analyzer connected to a Cascade Microtech probe station with 125-μm-pitch ground–signal–ground (GSG) probes. One port open-short-load calibration is conducted for a 50 Ω system impedance, and additional on-wafer open and short structures are used to move the plane of reference to the resonator's edge. Fig. 4 displays the photograph of the released device with lateral dimensions of approximately 625 μm^2. The initial as-grown frequency response of the resonator (excited mode 1) is provided in Fig. 4, where a modified Butterworth van-Dyke (mBVD) model [14] is fit to extract k_t^2 and Q values for the device, and (1) summarizes the equivalent electrical circuit model relations

$$Q_p = \frac{\omega_p L_m}{R_m + R_e} \quad Q_s = \frac{\omega_s L_m}{R_m + R_s} \quad k_t^2 = \frac{\pi^2 f_s (f_p - f_s)}{4 f_p^2}. \quad (1)$$

Table II lists the mBVD parameters for the first mode.

There are few reported studies that discuss the effects of polarization switching in the context of thin film membrane-suspended structures, specifically switching across a composite layer of AlN and ScAlN. It has been previously reported that ScAlN can be gradually polarization switched at a voltage less than the required coercive field through multiple cycles of switching pulses [15]. Fig. 5(a) shows the poling setup, where 150 V monopolar triangular waves with a rise and fall time of 100 μs for a number of cycles are applied across the resonator using two dc probes. Further investigation is required on the polarization switching of AlN–ScAlN piezoelectric–ferroelectric films, but a resonant third mode has been observed and plotted in Fig. 5(c) with a measured k_t^2 and Q_m values of 5.5% and 61, respectively. Moreover, as the number of cycles increases, there is also a gradual reduction and eventual disappearance of the first resonance mode (9 GHz). Measurement for the same resonator after polling showed that the polarization remained after a month. Compared to the simulation results, the figure of merit (FOM) of the reported resonator is lower than expected.
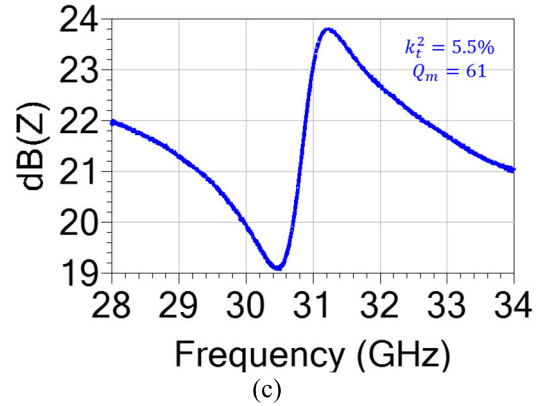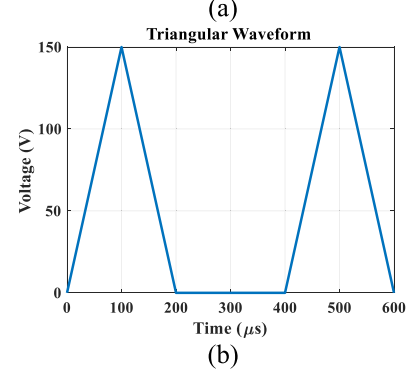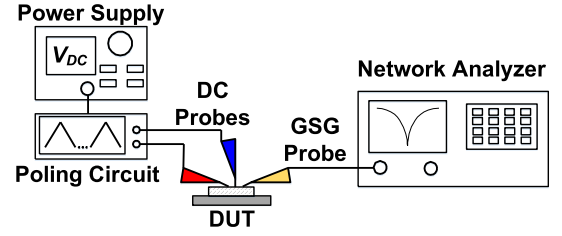

(a)

(b)

(c)

Fig. 5. (a) Measurement setup for polarization switching of the trilayer resonator. (b) Triangular waves are used to obtain (c) Mode 3 frequency response.

Compared to multilayer resonator designs with intermediate electrodes, the presented device enables a simple fabrication process and reduces the contribution of thermo-elastic damping losses from conductors in the overall quality factor [2]. Compared to existing overmoded bulk acoustic resonators at 30 GHz [16], the presented resonator exhibits higher coupling with a lower quality factor. Further improvement of the ScAlN growth conditions for better ScAlN crystallinity and domain orientation is underway and would significantly enhance the device's FOM. With optimization of the material parameters of the transduction layers, overmoded FBARs with high k_t^2 operating in the mm-Wave regime can be realized.

IV. CONCLUSION

In this work, a trilayer ScAlN FBAR operating at higher order mode in the mm-Wave regime is presented for the first time. The fabrication of the resonator requires only one deposition for the transduction layer, maintaining similar processing steps to fundamental mode FBARs. Through appropriate low-frequency bias across the electrodes, the device is capable of switching between fundamental mode at 9 GHz and higher

order mode at 31 GHz. Future work will be conducted toward the poling of these released structures, improved ScAlN/AlN layer growth conditions, and optimized layer thicknesses for best performance.

ACKNOWLEDGMENT

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