Multi Frequency Effect in Reversed c-Axis Polarity AlSiN film

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I. INTRODUCTION

For many applications, it is desired to grow AlN or other piezoelectric films in a reversed c-axis orientation to fabricate RSBARs (Reversed c-axis Series Bulk Acoustic Resonator) [1] or other acoustic devices with high coupling coefficient kt^2 & Quality Factor Q. An RSBAR has two piezo films, one with normal c-axis orientation (Type CP), the second with reversed c-axis (Type CN).

Previously investigated methods of growing reversed c-axis AlN were A) a reactive sputtering process starting from metallic mode with transition to deep poison mode, or B) reactive sputtering of AlN in a hydrogen environment [1, 2]. Both methods produced high quality films with reversed CN orientation, relatively high electro-acoustic coupling constant kt^2 and Q, but require two piezo films, harder in high volumes.

In this paper, we describe manufacturing of an integrated type CN/CP oriented AlN piezoelectric film, with Si dopant [3 - 9], which is potentially much simpler to do in high volume production.

AlSiN films not only exhibit reversed polarity relative to pure AlN, but also support higher harmonic frequencies that can be tuned via film stress. Across harmonics, Type CN AlSiN–based resonators achieve coupling coefficients comparable to those of Type CP AlN–based resonators. We hypothesize, that the mixed FBAR/RSBAR responses arise from a through-thickness polarity gradient (i.e., a depth-dependent CN/CP fraction) within a single AlSiN piezo film, rather than requiring two separately deposited piezo layers. This interpretation motivates the stress-dependent measurements and effective two-layer Mason modeling presented in this work.

II. METHODS/RESULTS

In this investigation we used an Advanced Modular Systems cluster tool with Mo, AlN and AlSiN deposition chambers, and an ion beam trimming module, see Figure 1.

The deposition chambers use standard dual conical magnetrons with AC deposition sources for AlN and AlSiN film deposition, or a DC deposition source for the Mo chamber, all sources are in a high-density plasma configuration. For AlN and AlSiN deposition, we used AC reactive sputtering. Frequency of the AC power source is 40 kHz, and the power may be varied over a 3 to 9 kW range. Wafer rotation was used to compensate edge to edge non-uniformity. An additional DC power supply was used for center to edge thickness uniformity improvement. Pure Al target rings with inserted Si plugs on a circle of 95 mm radius, were used to produce the AlSiN film composition.

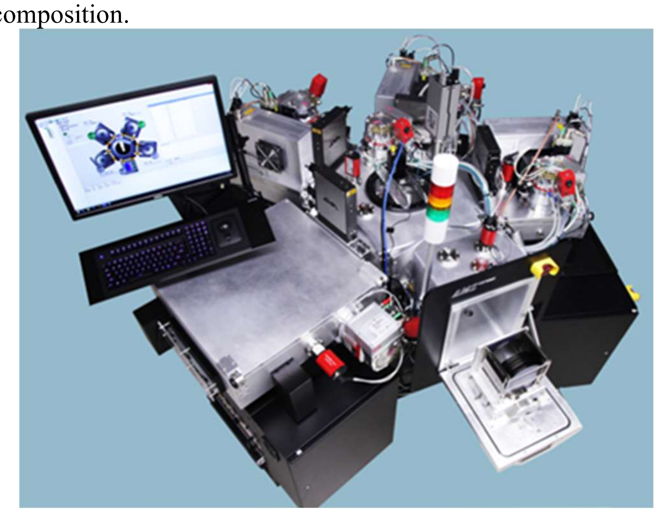

Figure 1- AMS Cluster tool with Trimming, AlN, AlSiN and Mo deposition chambers

The film deposition tool features a trimming module with a DC focused ion source with up to 6kV acceleration voltage. This module was used for substrate surface clean up before deposition, as well as to break crystallinity, and for smoothing the film surface after deposition of reversed CN oriented AlSiN, and before deposition of positive polarity AlN.

A standard HBAR device with 3000A of bottom Mo electrode thickness, blanket deposited either 5000A, 10000A, or 15,000A of AlSi(7%)N piezo thickness, and 3000A of top Mo electrode, were manufactured.

To contact the HBAR we use two ground pads and one signal pad, both patterned in the top Mo electrode, and a blanket (un-patterned) Mo layer underneath the AlSiN film. The ground pads are 375um x 400um. The signal pad is 90um x 90um, and the pitch for the structure is 150um. Measurements were done on Keysight E5063A NWA with 150um Form Factor probes, DC Bias Tee biasing with 70V DC power supply. The manufactured HBAR is shown in Figure 2.

To validate this measurement method & structure, type CP and type CN AlN films were deposited & evaluated by XRD rocking curve measurements, Si incorporation by SEM, and kt^2 coupling coefficient was obtained with the HBAR method. Results for a standard CP AlN film 1 um thick are: XRD <1.5 degree, and 7.6% coupling kt^2 for HBAR response.

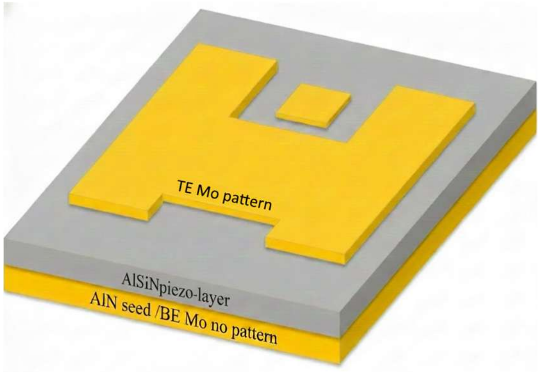

Figure 2 – Schematic of the electrode structure. Capacitive coupling, through oversized ground pads on top of the AlSiN film, is made to the bottom Mo layer. The extra capacitance is compensated during the data reduction of the acquired real & imaginary parts of HBAR device RF impedance.

Investigation of AlSiN films was done as follows:

A) Confirmation of the Reversed CN orientation of the sputtered AlSiN film was done in two ways:

- In Figure 3, the DC voltage shift coefficient (VoltCo) of FBAR resonant frequency was observed to be negative as compared to the positive coefficient found for type CP AlN films.

  The variation of VoltCo with position on the wafer is caused by the variation of stress across the wafer, as will be discussed later, see Figure 6. In regions of high compressive stress, this gives rise to the RSBAR type response demonstrated in Figure 5.

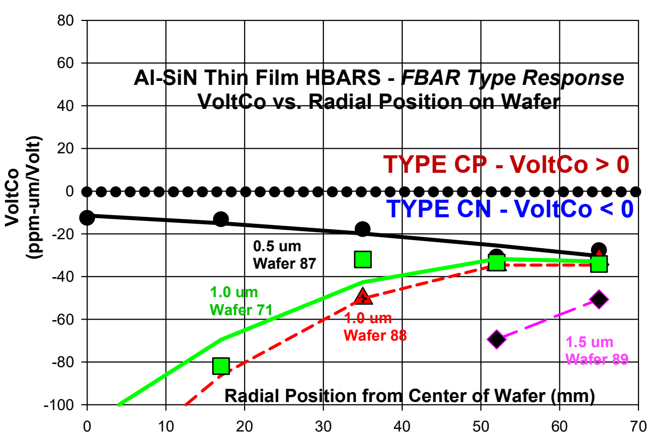

Figure 3 – Measured VoltCo Coefficient vs AlSiN Film Thicknesses, Type CN Polarity. Black 0.5 um, Red and Green 1.0 um, Pink 1.5 um thick

- Measurement of AlSiN film etch rate in dilute KOH (1:100)

  Results for etch rates of type CP AlN and CN AlSiN are shown in Figure 4.

B) Measurement of HBAR piezo coupling coefficient, kt^2: Network analyzer measured impedance data vs frequency show the presence of 2 types of modes & harmonics - see Fig. 5

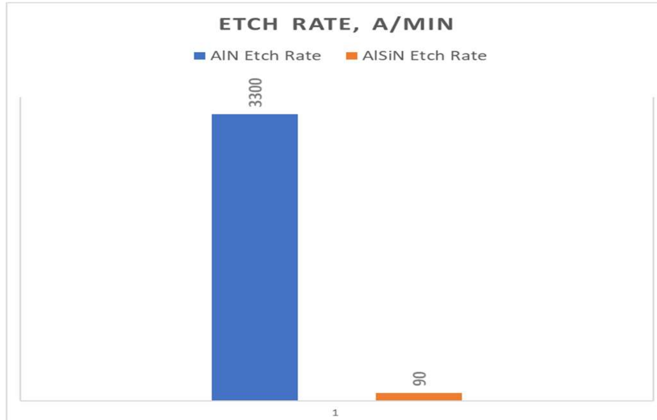

Figure 4- AlSiN and AlN etch rates in films in KOH solution. Type CN AlSiN has an etch rate more than 30 time slower than that of type CP AlN.

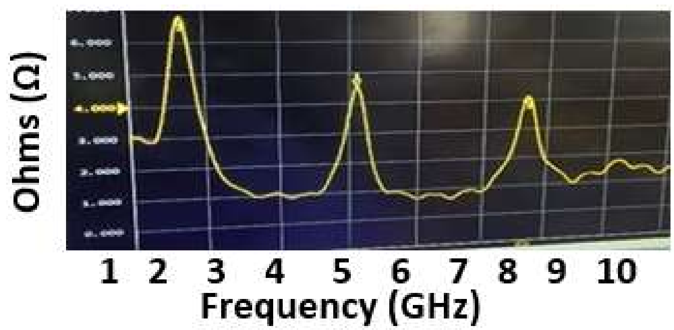

Figure 5 – Observed modes of a typical HBAR structure. A mixed CP/CN type piezo layer allows even (FBAR) and/or odd (RSBAR) modes and harmonics to be excited. See references [1,4] for discussion of the FBAR & RSBAR structures & modes. The simultaneous presence of FBAR-like and RSBAR-like modes in a single blanket piezo layer is consistent with a mixed-polarity response. In this work we interpret that mixed response as an effective through-thickness polarity gradient, which can be approximated in modeling as two sublayers with opposite effective piezoelectric sign.

These modes show strong FBAR response at the edges where the stress is tensile, and strong RSBAR response mid-wafer where the stress is compressive. Mixed mode response is seen near the center of the wafer, e.g. the device of Figure 5.

The effect of stress, causing large changes in piezo coupling constant, was first observed [10] in Lead Zirconate Titanate (PZT) ceramics, a precedent for such a hypothesis.

Also, from the various mixed mode frequency responses of a HBAR, it can be seen that the coupling coefficient depends on the stress in the AlSiN film. This result was confirmed on multiple wafers.

In order to further study the effect of wafer-to-wafer variation, as well as cross-wafer variation of stress, on mode coupling, AlSiN films with large stress variation across wafer were deposited. The resulting measured film stress is typically about 470 MPa tensile on the edge and about -480 MPa compressive in the center of the wafer, see Figure 6.

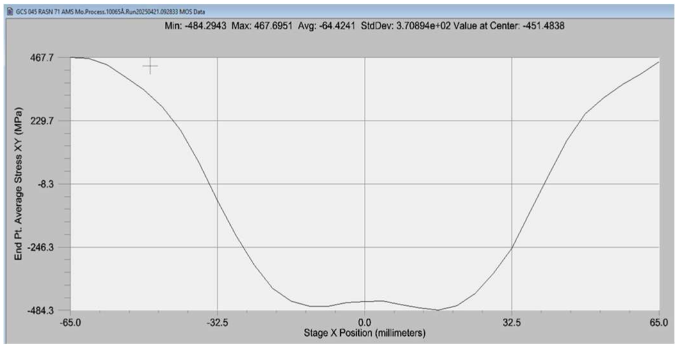

Figure 6 AlSiN film stress (MPa) across wafer

As can be seen in Figure 7, the AlSiN coupling coefficient for the first FBAR harmonic at 2.2 GHz (blue curve) is more than 5.5%, but does not reach a maximum. The third FBAR harmonic at 8.6 GHz (gray curve) has a similar stress behavior as for AlN film and requires more tensile stress (+250 MPa) to achieve maximum kt2 around 6.7%.

The second RSBAR harmonic (red curve) at 5.3 GHz for CN AlSiN, has clear maxima at about -100MPa compressive stress, and reaches 6.3% coupling coefficient, which is similar to the kt2 for CP AlN film, but for the first FBAR harmonic (low frequency 2.2 GHz).

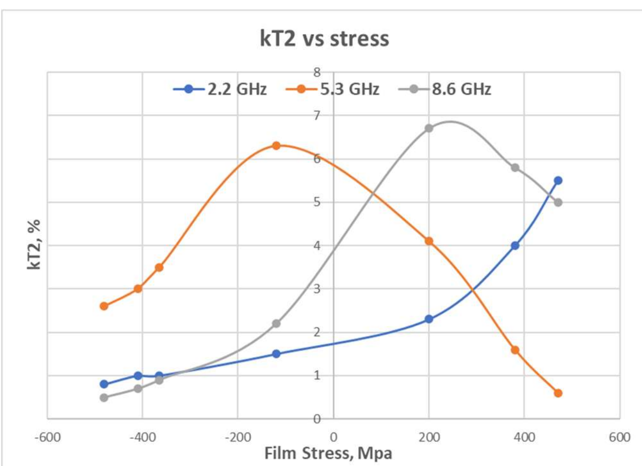

Figure 7 – Illustrating the stress dependence of the coupling constant FBAR mode and RSBAR mode coupling coefficients for AlSiN thin films, fundamental (first harmonic FBAR1 or RSBAR2) modes, & overtone (FBAR3) mode.

A circuit simulator analysis model was created to backfit to the measured data; Appendix A briefly describes the major assumptions of this model. Space does not permit a full description, only the best results in modeling representative FBAR or RSBAR data, taken from HBAR structures at three radial locations from center to edge, of each of the 3 wafers bearing a different film thickness.

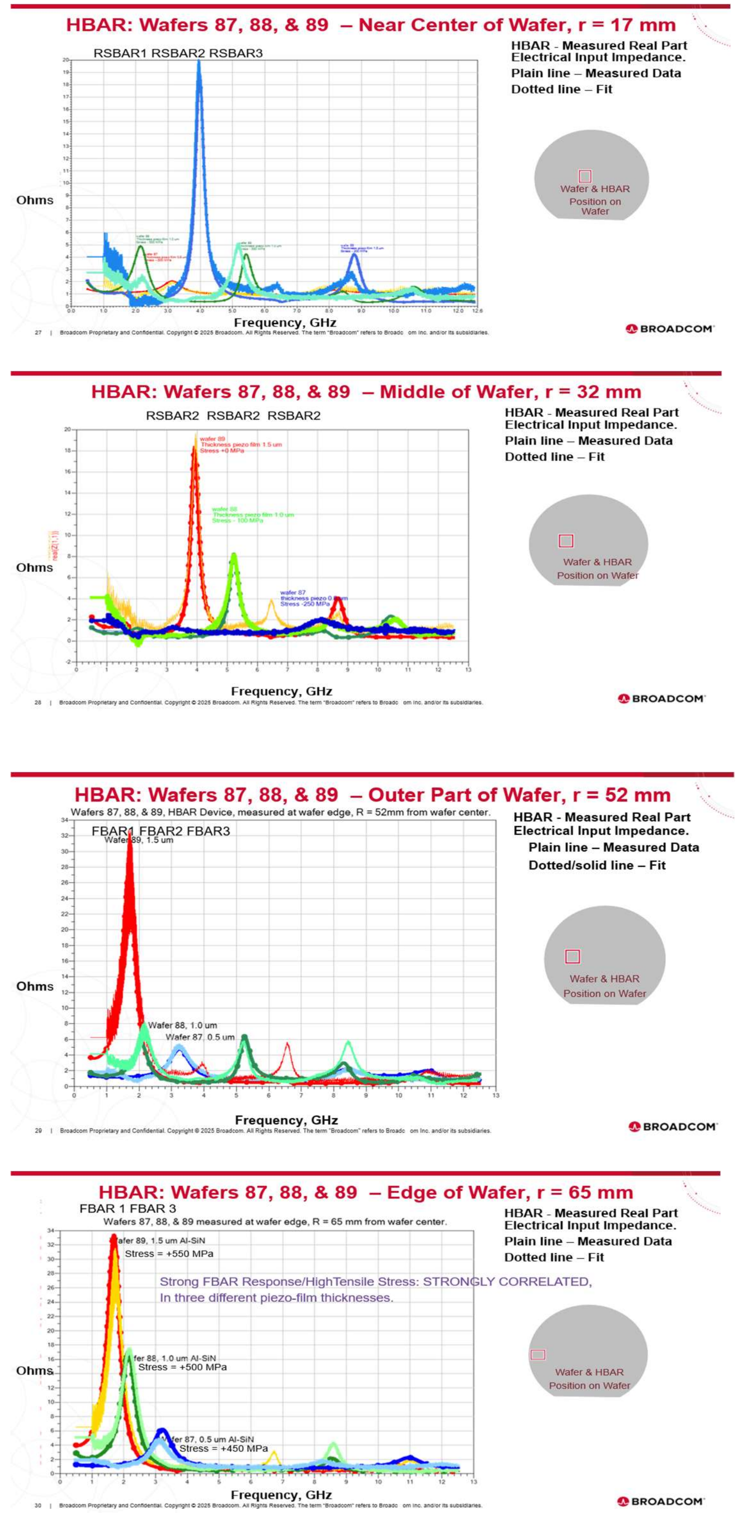

Figure 8 – Collage of measured and fitted reZ vs frequency results, for three AlSiN film thicknesses, taken at 4 different radial locations on the carrier wafers, shows how dramatically wafer stress affects the coupling to the FBAR or RSBAR modes respectively excited.

Effect of radial position on pure modes:

Figure 9(a)- radius 35 mm

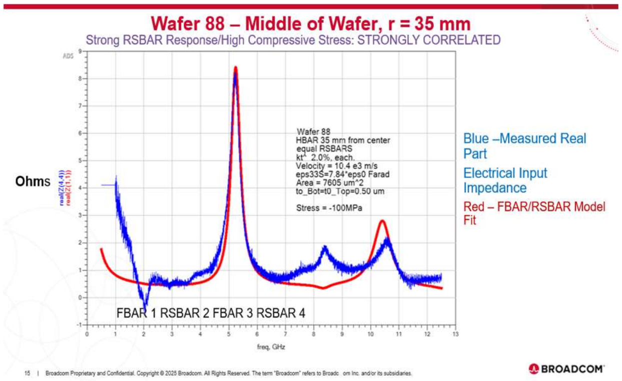

Figure 9(b)- radius 65 mm

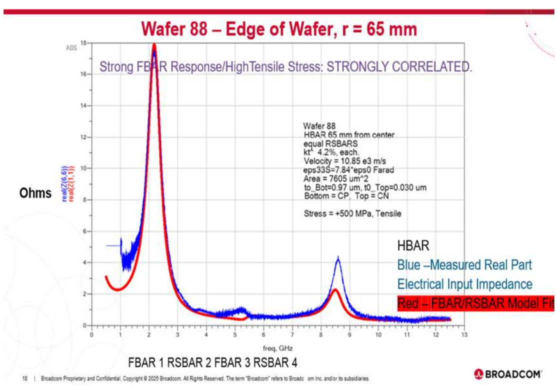

Figure 9 – For an AlSiN film thickness of 1.0 um, the dominant mode is dramatically changed from a pure RSBAR mode in Figure 9(a), to a pure FBAR mode in Figure 9(b), by moving from radial position 35 mm to radial position 65 mm.

III DISCUSSION/CONCLUSIONS

Stress plays a large role in determining the effective coupling of resonant acoustic modes in FBAR- and RSBAR-type devices. This effect is found to be robust across several film thicknesses. The observed FBAR/RSBAR mode content and extracted coupling exhibit a strong, repeatable dependence on film stress. The behavior is consistent with an effective mixed-polarity (CN/CP) piezoelectric response within a single AlSiN film. We interpret this mixed response as compatible with a through-thickness polarity gradient (i.e., a depth-dependent CN/CP fraction), and we model it using a two-layer Mason framework as an effective approximation of that gradient. Direct depth-resolved polarity measurements were not performed in this study and will be pursued in future work.

We have so far only done this work in unreleased AlSiN material, but expect that it would persist in SMR (solidly mounted resonators), and most likely also in released film structures (also known as FBARs).

It offers an exciting new way to fabricate RSBARs in one piezo film deposition, rather than the two-deposition method presented in [1], if one can control the stress to be compressive across an entire wafer.

Keywords—Aluminum Silicon Nitride, Aluminum Nitride, coupling coefficient, film stress

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Appendix A – Analysis Model

RSBAR/FBAR Model Using a Mason/Larson 1-D Model, in Advanced Design System (registered) Keysight Circuit Simulator

[1] The film is modeled as two effective sublayers to approximate a continuous polarity gradient through thickness; the fitted 'top' and 'bottom' layers represent the net contribution of polarity-domains within those thickness regions.

[2] For two piezo layers are assumed, each has a constant e33 but of opposite sign

[3] Each layer has an adjustable kt^2 coupling term, and a Nitrogen (Type CP normal polarity) piezo, or a Metal (Type CN reversed axis) piezo layers

[4] The 2 layers are assumed to be of unequal thickness, but total to the film thickness, as grown, e.g. 1 um. The coupling constants, kt^2 top and kt^2 bot, are not equal, but total some adjustable value around 5 to 10%.

[5] Molybdenum electrode layers, 0.30 um thick, each, top or bottom, for all 3 piezo film thicknesses.

[6] The input electrical impedance is measured or modeled at the electrical port. The Coupling polarity symbol will go with each plot.

Model of the HBAR device fabricated and analyzed in this work.