Characterization of Reversed c-axis AlN Thin Films

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Abstract —

Background: It is desired to grow AlN in a reversed c-axis configuration to fabricate R-FBARS (Reversed c-axis Film Bulk Acoustic Resonator) with reactively sputtered, thin film Aluminum Nitride (AlN).

Previous methods of growing reversed c-axis AlN, result in films with low electro-acoustic coupling constant, low Q, or inability to withstand the Avago Technologies FBAR release process.

Conribution/Methods: An AMS Inc. deposition tool, modified to allow independent control and unique processes, was used to deposit AlN on Al, Mo or W bottom electrodes used in this study.

AlN films of thickness 1.2 microns were deposited over patterned bottom electrodes, with additional processing used to reverse the c-axis of the AlN. A top electrode was deposited, patterned, and either processing stopped at the transducer point, or the R-FBAR was released from the silicon wafer with HF acid.

Results: The Avago Technologies Acoustic Imaging Microscope interferometer (AIM) is used in point mode to determine the AlN c-axis orientation. The transducer or R-FBAR is driven with a 40 kHz sine wave, and the phase of the top surface motion is observed. Both the orientation and the piezoelectric coefficient were determined.

To evaluate the material constants of the AlN for the R-FBAR structure, the input RF reflection coefficient vs frequency is measured. From a one-dimensional Mason model for the R-FBAR stack, the AlN material parameters – coupling constant k_t^2, resonant frequency, velocity, and attenuation, were determined by varying them in the model, to backfit the measured data.

R-FBAR resonators with reversed c-axis orientation, termed type CN ("Compression Negative"), as well as FBARS with normal c-axis orientation termed Type CP, ("Compression Positive"), were fabricated. A strong piezocoupling constant was observed, depending on the deposition parameters used.

The voltage shift ("Voltco") coefficient of the resonator resonant frequencies, f_S or f_P, was observed, compared to the interoferometric observations, and found to be a reliable indicator of c-axis polarity. For the FBARS and R-FBARS reported here, for the Type CP films, a Voltco of +40 kHz/Volt was observed, and for Type CN films, -30 kHz/Volt was observed.

Low frequency RBARS and high frequency RSBARS stacked resonator structures were fabricated, and preliminary results are given.

***Index Terms* — Thin film, AlN, piezoelectricity, reversed c-axis.**

I. INTRODUCTION

Aluminum nitride is a piezoelectric material in hexagonal crystal class 6*mm*. In the sputtered thin film form, AlN grows preferentially with its polar axis normal to the metal upon which it is grown, unless special process steps are employed. X-ray diffraction reveals that the films have well oriented crystallites in the (0001) direction, but the crystallographic a and b axes are randomly oriented. For single crystals, the c-axis polarity relative to any (0001) face can be easily determined, e.g., by etch pit decoration or interferometrically[1,2]. For thin film AlN, the c-axis polarity, relative to the metal surface on which it is grown, is determined at film deposition time and is difficult to change subsequently[3-5]. Characterizing reversed c-axis piezoelectric films is the subject of this paper.

There have been numerous methods to grow reversed c-axis AlN thin films reported in the literature [1, 3-5]. These methods produce encouraging evidence that the c-axis may be inverted, but generally do not produce high coupling constant material, or are not compatible with the FBAR technology developed at Avago Technologies [6-8].

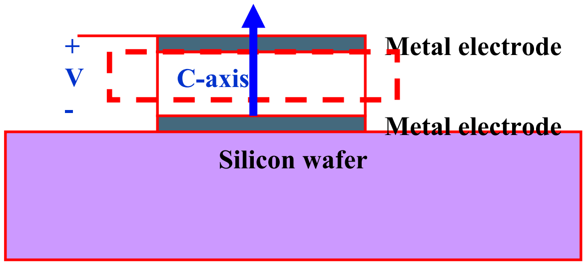
In this paper, we will present results for R-FBAR resonators made from reversed c-axis AlN films in an FBAR format.

II. REVERSED C-AXIS –
A. DEFINITIONS OF C-AXIS POLARITY OF ALN

When discussing thin films with possible positive or negative c-axis polarity with respect to the growth electrode as a datum surface, one needs a convention as to the c-axis orientation of the film, the direction of the applied electric field, and consistent with the observed motion of the film. In this work, we will always define the bottom electrode, on which the AlN is grown, to be both the electrical ground & the datum growth surface, so the positive E-field is applied conventionally as rising toward the driving electrode on top of the film, and the positive c-axis points up from the datum surface. As will be shown later, if a positive voltage is applied to the top electrode of a film with positive c-axis AlN, then the film will contract or compress. We term this AlN as Type CP, "Compression Positive". Likewise, if the c-axis is negative or reversed, pointing down toward the datum surface, the film will compress when driven by a negative voltage on the top electrode. This is termed to be Type CN AlN, "Compression Negative". In this convention, experiment has shown the Type CP material has the first nitrogen face on the bottom electrode, while Type CN material has the first aluminum growth face on the bottom electrode. See the 1949 IRE Standards on Piezoelectric Crystals [9] for a discussion of piezoelectric sign assignment conventions.

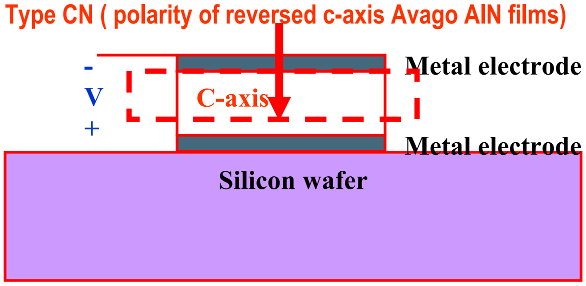
With the Type CP and CN definitions for AlN films, it is easy to relate measurements of surface motion to the sign and magnitude of the applied potential. Fig. 1 illustrates these conventions. We have used the Avago Technologies AIM [10] to carry out such studies in the point mode of operation.

In high Q FBARS (Type CP AlN), or R-FBARS (Type CN AlN), one can determine the c-axis type by applying a positive DC voltage (along with the RF voltage), to the top electrode, Type CP AlN (usual polarity of Avago AlN films)



Compression Positive (CP) –Film Compresses when a positive voltage is applied to the top electrode.

Type CN (polarity of reversed c-axis Avago AlN films)



Compression Negative (CN) –Film Compresses when a negative voltage is applied to the top electrode.

Fig. 1 - Illustrating the conventions for c-axis orientation, voltage, and compression of AlN films, for Type CP or CN.

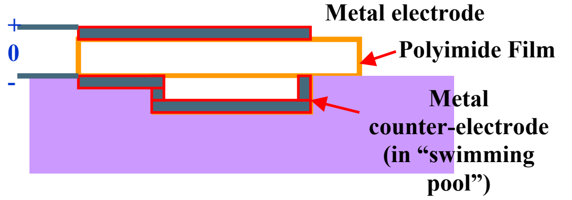
and observing the frequency shift of the resonator. For comparison, the c-axis orientation is also characterized by the interferometer before release. Type CP AlN material exhibits a positive (upshift) of frequency, while Type CN AlN exhibits a negative (downshift) of frequency. By introducing these conventions about growth surfaces and reference potential, we have created a framework in which one can and unequivocally determine the orientation of an AlN film, and can use low frequency measurements to non-destructively determine c-axis orientation & piezoelectric strength.

It is possible to grow either type of c-axis oriented AlN on a wafer. It would be useful to grow both types of c-axis oriented AlN films on a wafer, either one on top of the other or at lateral sites [11] .

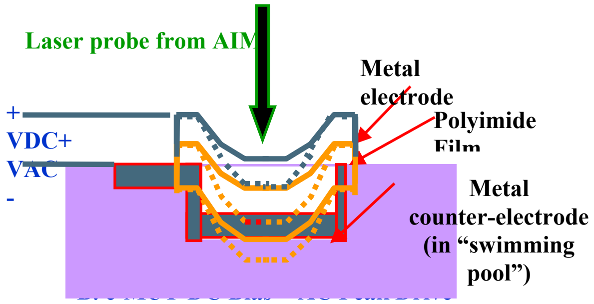
II. REVERSED C-AXIS ALN-

B. MEASUREMENT METHODS – INTERFEROMETER & C-MUT CALIBRATION TECHNIQUE

To determine the motion (compression or expansion) on application of an AC voltage to a piezoelectric film resonator, one needs a reference device that can be excited at low frequencies, and which can produce a known motion direction. A capacitive transducer (c-MUT) [12] provides a solution, because the electrostatic force between the electrodes is always attractive (compressive), regardless of the sign of the applied voltage. As shown in Fig.2, by applying a positive (or negative) DC bias voltage to the top electrode, a deflection of the membrane toward the bottom electrode occurs.



A. c-MUT-No Bias



Bias Voltage Applied. Equivalent to Compression.

* c-MUT-Courtesy of Prof. B.T. Khouri-Yakub, Stanford University, [11].

Fig. 2- Calibration an AC interferometer with a c-MUT transducer to determine sign and magnitude of the piezoelectric coefficient d_{33} .

If an AC voltage, e.g., 40 kHz, is superimposed on this DC potential, then when the AC is in its positive ½ cycle, the sum of the voltages will be even more positive, and the membrane will deflect even farther toward the bottom electrode. This appears to be *compressive stress* characteristic of a *Type CP* piezoelectric. The compressive motion will be in-phase with the 40 kHz drive, as seen by the AIM.

If the applied AC voltage is in its negative ½ cycle, then the sum of the DC bias voltage and the negative AC voltage will be less positive, and the membrane will move away from the bottom electrode. This appears to be an *expansion*, and the AIM records this as 180 degrees relative to the AC drive.

This technique is used to establish Type CP state, for the AIM operated in the point mode. The wafer bearing the c-MUT is set up on the AIM, a DC voltage on the order of +50 volts applied to the top electrode, and the phase of an applied AC driving signal (~1 volt peak) is adjusted until the interferometer signal in the phase sensitive detector/lock-in amplifier is 0 degrees. If the wafer is removed and replaced with no changes to the instrument, the same result is obtained.

Once this phase condition is established, the c-MUT wafer is removed and a wafer bearing AlN of unknown c-axis orientation is substituted. The phase and amplitude of the resulting AC signal are again observed. If the phase is 0^o, then it is Type CP material. If the phase is 180^o, it is Type CN.

Since the AIM is calibrated to read surface peak displacement in nanometers, the piezoelectric film displacement can be measured. The ratio of measured peak displacement to peak driving voltage yields the piezoelectric coefficient d_{33} [13].

III. REVERSED C-AXIS ALN FILM GROWTH & EVALUATION

We grow Type CN or CP AlN thin films, evaluate them for the sign and strength of the piezoelectric constant, and then measure the material and piezoelectric material properties.

We deposit standard (POR) AlN by reactively sputtering an aluminum target in an argon/nitrogen atmosphere. In the AMS Inc. AlN sputtering tool, one loads a wafer into a first chamber which is evacuated to remove atmospheric contaminants, then through a load-lock door into the deposition chamber. Process gases are admitted, the sputtering is initiated by applying RF power to create an ionized atmosphere to deposit the AlN film, and a laser interferometer monitors the thickness.

A. UNRELEASED TYPE CN ALN FILMS

In the first technique to fabricate Type CN AlN, a flash of metallic aluminum was deposited over the bottom electrode by sputtering the AMS aluminum target in pure Argon for a few seconds. The nitrogen flow was then turned on, which switched the plasma to a specified argon/nitrogen ratio at a controlled pressure and mixture. AlN grows on the fresh aluminum layer as high coupling constant Type CN material.

This is illustrated by Fig. 3, which presents AIM interferometer differential phase measurements made on AlN films: a) Type CP grown on Molybdenum, and b) Type CN grown on an aluminum metal flash over Molybdenum without breaking vacuum. In both cases the Mo was on glass (PSG) over silicon, unreleased, so a low Q transducer response was seen. From the measured displacement & driving voltage, the piezoelectric coefficient & sign were determined.

Fig. 4 illustrates the measured $d_{33}^{(CN)}$ for the unreleased Type CN AlN films, expressed as an electro-acoustic coupling constant, k_t^2, relative to the measured $d_{33}^{(CP)}$ value, which is ~ 6 pm/volt [13].

As the thickness of the aluminum flash layer increases, the coupling coefficient increases. Figure 4 also illustrates the measured phase shift for the Type CN AlN, another indicator of the degree to which the c-axis was reversed. From this and the known growth condition of an aluminum flash, one concludes that Type CN material is aluminum face first type.

These results illustrate that 1) Type CN AlN can be grown as a transducer, and 2) the AIM measurement technique works.

It was found that released R-FBAR resonator structures could be built with aluminum seed layers, but the final HF release step tended to destroy the aluminum seed film and float off the R-FBAR. To solve this problem, our approach was to pattern the AlN/Mo/Al seed /stack, then apply a sealing layer of protective material around the edges of the aluminum seed was deposited and patterned, and the FBAR was successfully released in 10:1 hydrofluoric acid, producing an R-FBAR.

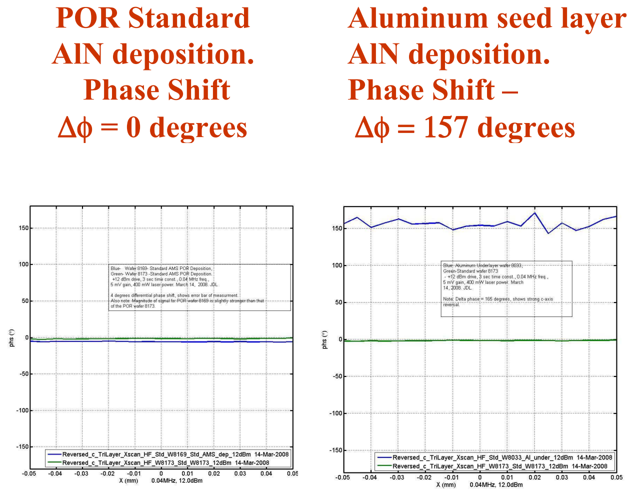


Fig. 3 – Phase shift: a) left panel-Type CP AlN grown by the standard POR process, and b) right panel-Type CN AlN grown over an aluminum metal flash without breaking vacuum.

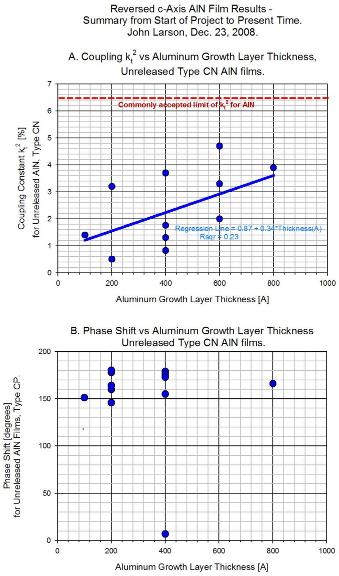


Fig. 4 –Type CN AlN is grown over an aluminum metal flash. AlN film is not released. Coupling constant (top panel) and relative phase shift (bottom panel), vs. aluminum thickness, are plotted.

B. – RELEASED TYPE CN ALN RESONATORS

Another approach to growing R-FBARS was to change the process gas proportions to provide a seed or a reduced surface on which to grow the Type CN material. This approach was much more successful. We now report on R-FBARS made on molybdenum electrodes, fully released from the silicon substrate, & exhibiting high coupling/Q resonators.

It was noticed that one could grow Type CN AlN on tungsten electrode material with the same type of process. We suspect, but have not proven, that this process will produce Type CN AlN on many other metals, such as ruthenium, vanadium, tantalum, titanium, copper, gold, silver, etc., because the seed metal electrode growing surface may be reduced and seeded.

IV. R-FBAR RESULTS

A. COUPLING CONSTANT, MATERIAL PROPERTIES

Released R-FBAR resonators were fabricated in the Avago FBAR process on molybdenum electrodes over PSG glass and silicon. The typical stack is shown in Table 1.

Stack	**Thickness**
Top Molybdenum	**3077 A**
AlN- Type CN	**12,000A**
Bottom Molybdenum	**4393 A**

TABLE 1- R- FBAR STACK.

Individual die with 30 kmicron^2 area, reactive impedance ~ 50 Ohms, are probed on-wafer with a Cascade Technologies microprobe connected to an Agilent Technologies E5071B network analyzer. This combination is calibrated to a set of standards. The reflection coefficient S_{11} (f) is measured over a frequency range 0.1 to 8.5 GHz.

To reduce the data, a one dimensional Mason model [14-16] simulator, implemented in Agilent Advanced Design System (ADS) software, is used to calculate the expected reflection coefficient vs frequency. The mechanical and piezoelectric AlN material constants in the model are varied to fit the calculated to the measured reflection coefficient data.

Fig. 5 shows the broad band refection coefficient result for a typical R-FBAR. One sees a high Q resonance at 1600 MHz, and the first overtone resonance at ~ 6GHz.

For the R-FBAR of Fig. 5, the coupling constant k_t^2=5.81%, and the parallel resonance Rp = 1756 Ω**.** For comparison to the typical FBAR made from Type CP AlN, the coupling coefficient k_t^2 = 6.3%, Rp ~ 2500 Ω.

B. VOLTAGE SHIFT OF RESONANT FREQUENCY

When a DC or low frequency AC voltage is applied across the AlN layer in a high Q FBAR resonator, a small frequency shift occurs in both the series and parallel resonant frequencies. This change is of the order 10 to 100 part per million, which can only be observed in a high Q resonator. The shift reverses if the opposite sign of voltage is applied.

The effect is dependent on the type of AlN, the E-field in the AlN layer, and on a field dependent piezoelectric constant. The frequency is altered by changes in the stiffened velocity of sound due to changes in the piezoelectric constant (major), and by piezoelectrically induced changes in the thickness of the AlN (minor). Since the effect is dependent on the electric field (V/to) in the AlN, thinner AlN results in a larger "VoltCo", which is defined as the change in frequency per volt applied.

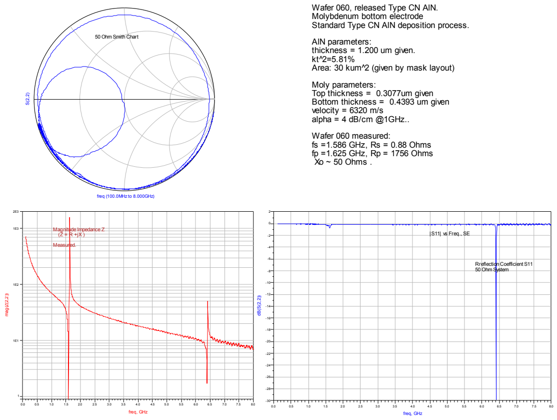


Fig. 5-Illustrates the broad band reflection coefficient for a Type CN R-FBAR. Note the high Q, high k_t^2 resonances, quite comparable to those obtained for a Type CP FBAR.

VoltCo is measured by applying both a DC voltage and an RF signal, via a RF/DC blocking component, to the top electrode of the resonator & measuring the frequency shift. Typical values for R-FBARS are: VoltCo_{CN} =-30 to -40 kHz/Volt, and for FBARS: VoltCo_{CP} = +40 kHz/Volt.

The coupling constant was varied by changing the AlN deposition conditions. Fig. 6 illustrates the data, and a linear relation of VoltCo vs coupling constant k_t,. The effect can be summarized as a voltage dependent piezoelectric constant $e_{33}(V)$:

$$e_{33}(V) = e_{330}\,[1 + \alpha^*\,(V/t_0)] \qquad (6)$$

in which e_{330} is the piezoelectric constant in Coulomb/m^2, α expresses the electric field dependence, t_0 is the AlN film thickness, and the stiffened sound velocity is:

$$v_0^D = v_0^E * (1 + k_t^2)^{1/2}\,. \qquad (7)$$

From these relations and a standard definition of k_t^2, the change in parallel resonance frequency Δf_p per volt is:

$$\Delta f_p / \Delta V \sim f_p\, k_t^2\, \alpha / t_0 = \mathrm{VoltCo} \qquad (8)$$

For the 1.2 micron thick AlN samples measured here:

$$\alpha_{CN} = -547 \text{ pm/V} \qquad (9)$$

$$\alpha_{CP} = +476 \text{ pm/V} \qquad (10).$$

C. TEMPERATURE COEFFICIENT OF FREQUENCY

The temperature coefficient of frequency was measured for R-FBARS over the range 20 to 120 degree C, and found to be -33 ppm/degree C, slightly greater than that for Type CP films.

V. APPLICATIONS –A. RBAR

The effect of a Type CN AlN film is only apparent in the presence of a Type CP film, for example in a side by side configuration such as a FACT transformer [11], or in a stacked resonator format, for example an RBAR or an RSBAR[17].

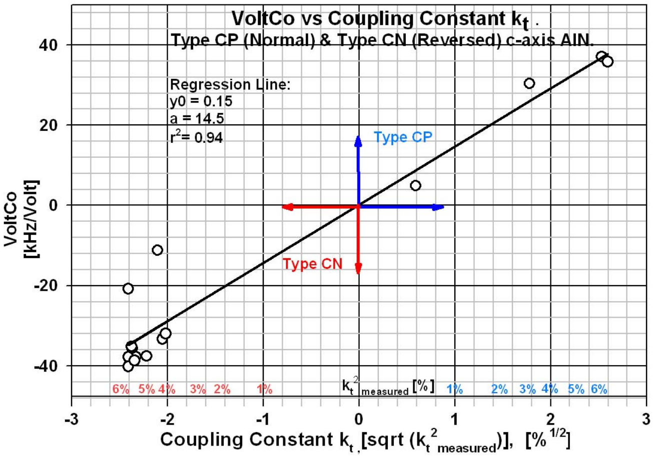


Fig.6-VoltCo vs coupling constant $(k_t^2{}_{measured})^{1/2}$ exhibits a linear relationship. Coupling k_t is varied by growth conditions.

An RBAR is stacked resonator with a bottom Type CP FBAR, and a top Type CN R-FBAR, or vice versa. Fig. 7 illustrates the RBAR stack (left), in comparison to a single FBAR (top) and DBAR (same c-axis type of AlN, right). The RBAR is driven from the center electrode, with the top and bottom electrodes grounded, paralleling the two resonators to decrease the area for a given resonator impedance, e.g., 50 Ω.

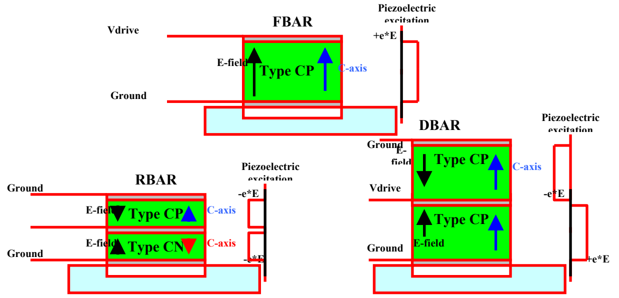


Fig. 7 – Comparison of a standard FBAR (top) and stacked resonators RBAR (left) and DBAR (right) as to electric field / c-axis orientation & effective terminal impedance.

The piezoelectric excitation, product of driving electric field and the signed e_{33} coefficient are indicated schematically for each resonator. The FBAR has a ½ wave length thickness piezoelectric excitation, and by driving it from the outside electrodes, the two halves of the structure (each with impedance ½ Xo) are connected in series, resulting in an input impedance of Xo. The RBAR is also a half wave length piezoelectric excitation due to one layer having a reversed c-axis sense, but by driving it from the center electrode, one gets a parallel connection of the two resonators, resulting in an input impedance of ¼ Xo. This is a factor of 4 reduction in impedance for a given die area.

RBARS were built in both configurations, with 1.2 um of AlN in each resonator. Fig. 8 shows the real part of the measured resonator impedance for the RBAR at 1.2 GHz, 36 kum^2 area, Xo ~ 22 Ω, followed by a weak FBAR response at double the frequency, 2.4 GHz, due to the imbalance in coupling constant between the top & bottom resonators.

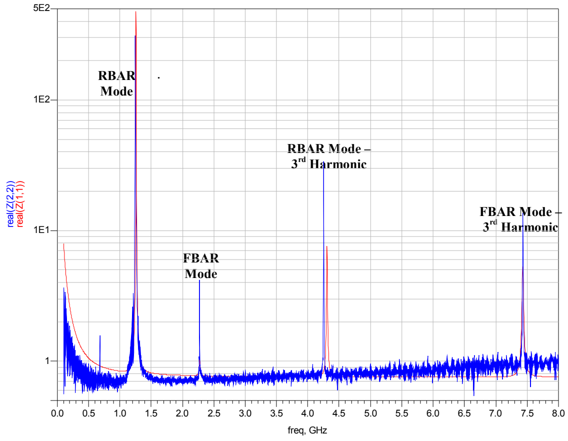


Fig. 8 – Illustrates the real part of impedance for an RBAR resonator. Bottom: Type CN, k_t^2 bot = 5.5%; Top: Type CP, k_t^2 top = 6.5%. The FBAR response is non-zero, due to k_t^2 imbalance.

B. RSBAR

RSBARS are stacked resonators with both AlN types[16]. Figure 9 illustrates two possible RSBAR configurations.

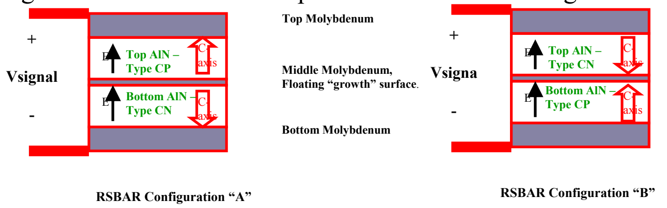


Fig.9 – Schematic diagram of RSBAR configuration.

Devices were built in both configurations, with 0.6 um of AlN in each resonator. This doubles the frequency, as compared to that of the standard FBAR with one type AlN throughout the stack, and thickness 1.2 um. If the comparable FBAR were made ½ as thick to get the same frequency, the RSBAR impedance would be twice that of the FBAR.

Fig. 10 shows the real part of the measured RSBAR resonator impedance. There is a strong RSBAR fundamental response at 4.5 GHz, and a very weak FBAR response at half the frequency, 2.1 GHz, due to unbalanced coupling constants.

VI. DISCUSSION & CONCLUSIONS

We describe a method to characterize the c-axis polarity of thin film piezoelectric films. An AIM method to differentiate Type CP or Type CN AlN films is introduced. For quantitative determination of the piezoelectric constant of an R-FBAR resonator, a voltage/frequency shift method is given, which correlates 100% to the results of the AIM method.

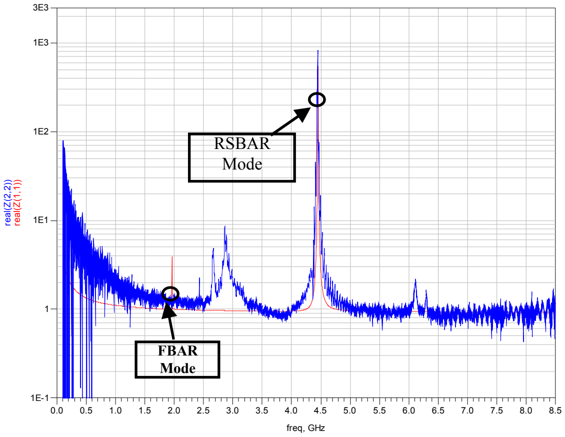


Fig.10 – Real part of impedance for an RSBAR resonator. Config.: Bottom: Type CP, k_t^2= 6.3%, Top: Type CN AlN, k_t^2= 5.8%.

Two methods to deposit Type CN films were used successfully: 1) aluminum seed layer, 2) surface reduction.

Released AlN R-FBARS were fabricated. RF reflection coefficient measurements were made and a Mason model backfit to these data, yielded coupling constants k_t^2 =5.8%, VoltCo = -30 kHz/Volt, and TempCoFrequency =-33 ppm/deg C, comparable to those for FBAR resonators.

One gains an advantage if both types of AlN are present, for example in FACT transformers [10]. To demonstrate mixed stacked resonators, two novel devices are presented, an RBAR low frequency stack, and an RSBAR high frequency stack.

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