# Low Loss, Wideband 5.2GHz BAW RF Filters Using Single Crystal AlN Resonators on Silicon Substrates

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**Bulk Acoustic Wave, RF Filters, 5G, WiFi, AlN, Resonators**

**In this work, the authors report single crystal aluminum nitride (AlN) bulk acoustic wave (BAW) resonator and filter technology in the 1-6GHz range for cellular, WiFi and high frequency and high power applications. 5.2GHz BAW filters, utilizing undoped single crystal AlN, are reported. Measured 5.2GHz filters had an absolute 4dB bandwidth of 210 MHz, a minimum insertion loss of 2.0 dB and rejection >30 dB. 5.2GHz resonators show $k^2_{eff}$ of 6.07%, Qmax of 1497, and FOM of 91.**

## INTRODUCTION

A demand for broadband, high speed data transmission is leading to the emergence of Wi-Fi spectrum in the 5GHz to 6 GHz frequency ranges [1]. Tri-band routers delivering to IEEE 802.11ac are capable of multiple gigabit speeds by transmitting at 2.4 GHz and two 5 GHz bands. Current routers support UNII 1+2A (Fig.1) and UNII 2E channels [2] and require small form factor coexistent filters above 5GHz. While some experimental micro electro-mechanical systems (MEMS) devices have shown promising performance at these frequencies [3], incumbent filter technologies are based on surface acoustic wave (SAW) and bulk acoustic wave (BAW) resonators. These high frequencies are challenging for traditional compact RF filters fabricated from SAW devices due to small width and pitch required of the interdigitated fingers [4]. Therefore, acoustic filters based on BAW resonators are expected to deliver the required performance with very small footprints (<4mm2).

Film bulk acoustic resonator (FBAR) [5] and solidly mounted resonators (SMR) [6] are the two dominant BAW resonator technologies currently utilized in RF filters due to their compact size, high Q-factor, high operating frequency, and good power handling. Today, FBAR and SMR BAW resonators are constructed by depositing poly-crystalline aluminum nitride (AlN) piezo-electric thin films via physical vapor deposition (PVD) techniques. By contrast, AlN epi films used in this work are epitaxially grown via Metal-Organic Chemical Vapor Deposition (MOCVD) and resonators are fabricated on 6-in silicon substrates.

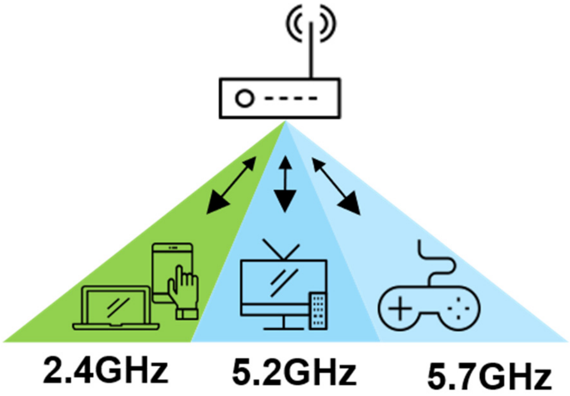

**Figure 1**: Tri-Band WiFi router configuration requiring 2.4GHz, 5.2GHz and 5.7GHz radios. The 5.2GHz spectrum includes UNII-1+2A band, covering 5.17-5.33GHz frequency band.

## ADVANTAGES OF SINGLE CRYSTAL ALN

Single crystal AlN films grown by MOCVD on SiC substrates have quantifiable higher crystal quality compared to poly-crystalline PVD AlN, as seen by (0002) X-ray diffraction (XRD) rocking curve full-width half-maximum (FWHM) of 0.027∘, compared to typical FWHM of 2-3∘ in PVD AlN. This improved crystal quality has been demonstrated to result in improvements in acoustic velocity [7] and potentially improved piezoelectric coefficients [8]. Higher longitudinal acoustic velocity in the AlN piezo-material allows thicker materials for the same frequency. It is reported [9,10] that thermal conductivity of polycrystalline AlN thin films degrades as film thickness decreases, which may constrain the power handling capability of traditional FBAR at higher frequencies.

These factors of improved acoustic velocity, potentially improved piezo-electric coefficients, and improved thermal conductivity suggest that BAW filters constructed using single crystal, epitaxially grown MOCVD-AlN offer performance advantages (insertion loss, bandwidth and skirt steepness) over PVD-AlN based BAW filters, especially for high frequency and high power applications.

Previous literature [11]–[15] demonstrated excellent results using PVD-AlN for high frequency applications. Work using single crystal (MOCVD) Group III-Nitride films for BAW resonators [16-20,21,23] is summarized in Table 1.

TABLE I
Single Crystal Group III-Nitride Bulk Acoustic Resonators

| **Ref.** | **XRD** | **Stack** | **Freq** | $k^2_{eff}$ | $Q_{max}$ | **FOM** |
|---|---|---|---|---|---|---|
| | | | GHz | % | | |
| 16 | – | GaN/ AlN | 1.1 | 5.0 | – | – |
| 17 | 0.23° | GaN | 6.3 | 3.4 | *1130 | 38 |
| 18 | 0.36° | GaN | 2.1 | – | *424 | – |
| 19 | 2.4° | AlN | 3.7 | 1.1 | *1557 | 17 |
| 20 | 0.37° | $Al_xGa_{1-x}N$ | 2.3 | 4.44 | 1277 | 57 |
| 21 | 0.025° | AlN | 3.8 | 7.63 | 858 | 66 |
| 23 | 0.027° | AlN | 5.2 | 6.32 | 1523 | 96 |
| This work | 0.028° | AlN | 5.2 | 6.07 | 1497 | 91 |

*In this work, Q-factor is calculated from the full mBVD model following [22]. Note [17] [18] [19] quote $Q_r$ which uses only the motional arm of the mBVD model.

## Device Technology

Single crystal epitaxial piezoelectric layers were grown via conventional MOCVD. The growth structure comprises AlN of 0.7 µm thickness (nominal target) and the resonators are fabricated on silicon (Si) substrates. A 11-mask level, two-sided wafer process, including sputter-deposited electrode metals and a substrate thinning process yielded resonators with two air interfaces. Backside resonator electrode was routed to the topside of wafer by vias in the AlN thin film. A schematic diagram showing the structure of the fabricated resonators is shown in Fig. 2.

## Resonator Results

The measured S-parameters of the 1-port resonator are collected on-wafer via air coplanar GS probe measurement using a Rhode and Schwarz ZNB20 vector network analyzer. The manifold present between the intrinsic resonator and the measurement probe plane is de-embedded by subtracting an equivalent measured open and short structure, representative of the measured DUT.

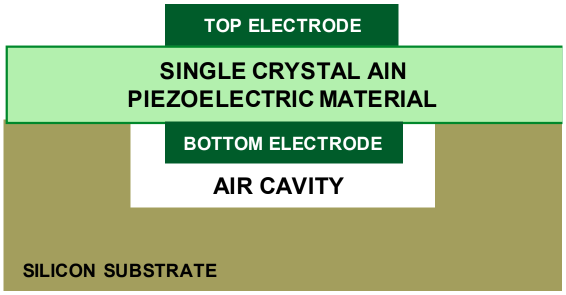

**Figure 2**: Cross-section of the fabricated resonators, showing top and bottom electrodes on single crystal AlN piezoelectric material, fabricated on a high resitivity silicon substrate.

The measured and de-embedded data was fit to a modified Butterworth Van-Dyke (mBVD). The mBVD model parameters were obtained by a simultaneously optimizing the fit to measured S and Y characteristics as well as Bode Q-factor plot (Fig. 3).The resulting fit and model is shown in Fig. 3 & 4. The resonant frequency (fs) and anti-resonant frequency (fp) were extracted from the zero crossing of phase of the de-embedded resonator Y-parameters and determined to be 5.264 GHz and 5.401 GHz respectively. The calculated value of $k^2_{eff}$ was 6.07%.

The Bode plot (Q-factor vs. frequency) of the de-embedded measured resonator is shown in Fig. 4. The Q-factor obtained from the fitted mBVD model was evaluated using the method described in [22]. Based on the modeled Bode plot, the $Q_S$ was found to be 876, $Q_P$ was 1125 and Qmax was 1497. This translates to a figure of merit of 91.

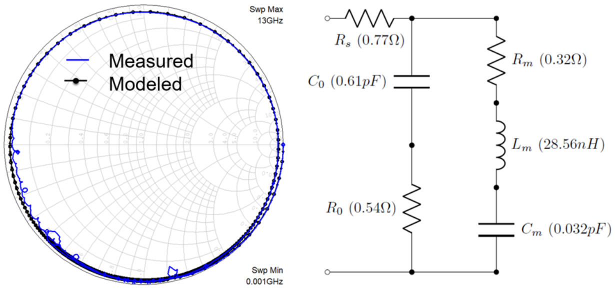

**Figure 3**: Measured S parameter (“Q-circle”) with mBVD model result overlaid, showing excellent agreement between model and measured data. Schematic and values of the mBVD model are shown to the right.

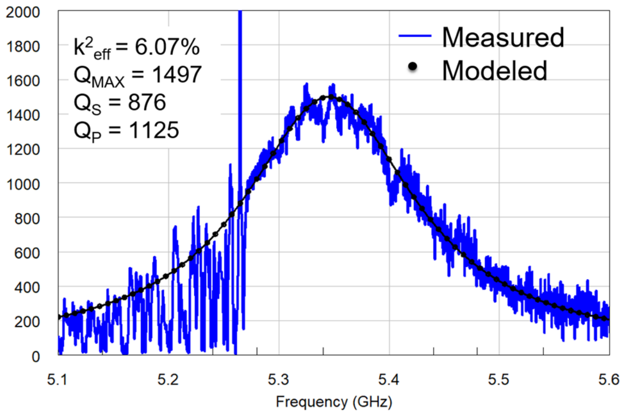

**Figure 4**: Bode plot showing Q-factor vs frequency. The blue trace is based on the measured and de-embedded S-parameter and the black trace is based on the mBVD model fit to measured data.

## MEASURED FILTER RESULTS

A half-ladder network filter was designed in AWR Microwave Office using a calibrated modified Mason model of the single crystal acoustic resonator. The design consisted of 9-elements, 4-series and 5-shunt elements. The design contained 6 unique resonators in series and 10 unique resonators in shunt path. Fig. 7 shows a 3D model of the measured filter die, the die size on wafer is 0.7 mm$^2$. A brief comparison of the measured filter performance versus other BAW based 5.2 GHz filters is shown in Table II.

A plot of the measured filter passband response is shown in Fig. 5, demonstrating a minimum insertion loss (IL) of 2.0 dB, an average IL of 3.14 dB, center frequency of 5.24 GHz, and absolute 4 dB bandwidth of 210 MHz. The passband skirt rolloff is -1.8 dB/MHz on low frequency side. A wide band plot of the filter performance (S21) is shown in Fig. 6 and shows out of band rejection better than 28.5 dB at 5.88GHz.

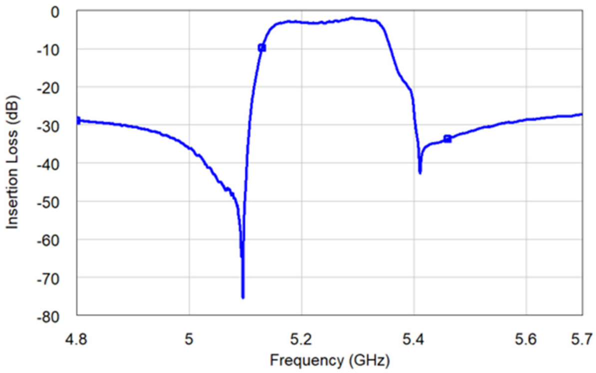

**Figure 5**: Measured narrow band S21 (die level) for the fabricated 5.2 GHz filter, showing minimum insertion loss of less than 2dB and 210 MHz of 4dB bandwidth.

It is worth noting that rejection measured at the die level typically improves by more than 10dB after packaging, as the filter design includes both die and package.

TABLE II
HIGH REJECTION 5.2GHZ BULK ACOUSTIC WAVE FILTERS

| **Ref.** | **Stages** | **Reject (dB)** | **Mean IL (dB)** | **4dB BW (MHz)** |
|---|---|---|---|---|
| 13 | 4 | 20 | ≈1.8 | >230 |
| 15 | 3.5 | 25 | ≈2.5 | 170 |
| 23 | 5.5 | 38 | 3.36 | 151 |
| This work | 4.5 | 28.5* | 3.14 | 210 |

* Rejection measured at the die level typically improves by more than 10dB after packaging.

## CONCLUSIONS

Bulk acoustic wave (BAW) filters operating at center frequency of 5.2 GHz, comprising of BAW resonators utilizing single crystal aluminum nitride (AlN) piezoelectric films based upon a silicon substrate platform are reported. MOCVD growth was used to obtain high quality single crystal AlN films scalable to resonator frequencies up to 7GHz. Such films exhibit (0002) X-ray diffraction (XRD) rocking curve full-width half-maximum (FWHM) of 0.028°. The fabricated filters reported here had a center frequency of 5.2 GHz and absolute 4dB bandwidth of 210 MHz, a minimum insertion loss of less than 2dB, an average insertion loss of 3.14dB and out of band rejection greater than 28.5dB measured at the die level. Realized filter die sizes were 0.7 mm$^2$ which is less than a tenth of the size of resonant cavity filters that currently are used in WiFi routers. Resonators on

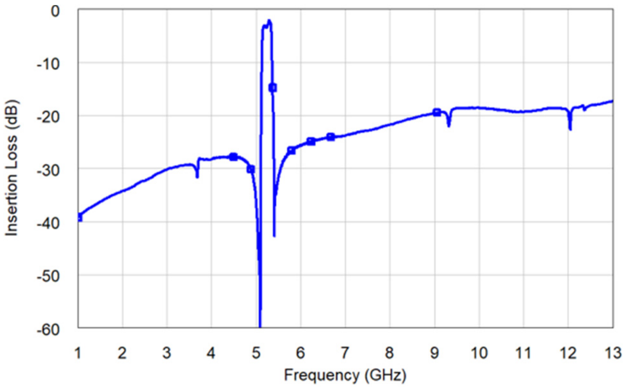

**Figure 6**: Measured wide band S21 for the fabricated 5.2 GHz filter, showing out of band rejection better than 28.5 dB. It is worth noting that rejection measured at the die level typically improves by more than 10dB after packaging.

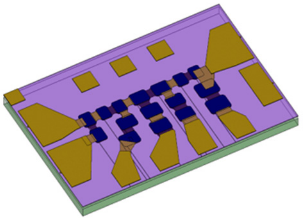

**Figure 7**: 3D model of the 5.2GHz bandpass filter die.

the same wafer show an electro-mechanical coupling as high as 6.07% and maximum Q-factor up to 1497. This is a demonstration of single crystal AlN based BAW resonators constructed using Si substrates and filter technology at 5.2GHz enabling small form factor and high performance filter solutions for high frequency Wi-Fi and UNII band infrastructure applications.

## ACKNOWLEDGEMENTS

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## ACRONYMS

BAW: Bulk Acoustic Wave