PRESENTED ON DECEMBER 10, 2019 AT THE 2019 IEEE IEDM, SAN FRANCISCO, CA

452 MHz Bandwidth, High Rejection 5.6 GHz UNII XBAW Coexistence Filters Using Doped AlN-on-Silicon

Y. Shen, P. Patel, R. Vetury and J.B. Shealy
Email: jshealy@akoustis.com
Akoustis Technologies Inc., Huntersville, NC USA

Abstract—5.66 GHz bulk acoustic wave filters, utilizing doped aluminum nitride (AlN), are reported. The filters exhibit high -3 dB bandwidth of 452 MHz (8% fractional bandwidth), a minimum insertion loss of 1.79 dB, rejection greater than 50 dB and power handling performance (near the upper band edge) up to 32.5 dBm. Resonators show k^2eff of 10.24%, Qmax of 1479, and FOM of 151.

Index Terms—RF Filters, Mobile communication, Piezoelectric devices, Electromechanical devices, Wide band gap semiconductors, bulk acoustic wave resonators, UNII, acoustic filters, coexistence, BAW filters, WiFi.

I. Introduction

A demand for broadband, high speed data transmission is leading to the emergence of Wi-Fi spectrum in the 5 GHz 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 WiFi routers support UNII 1+2A and UNII 2C+3 channels as shown in Fig. 1 and require small form factor coexistent filters above 5 GHz as the complexity of Multi-User MIMO continues to grow. A key challenge to addressing the UNII 2C+3 band is achieving the bandwidth of 360 MHz while successfully coexisting with signals in the nearby UNII 1+2A band. While some experimental micro electro-mechanical systems (MEMS) resonators have shown impressive electro-mechanical coupling near these frequencies [2], they exhibit low quality factor preventing coexistence filter performance near the passband. Other 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 [3]. Therefore, BAW RF filters are the logical choice to explore true coexistence performance at high frequency with very small footprints.

Film bulk acoustic resonator (FBAR) [4] and solidly mounted resonators (SMR) [5] 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 piezoelectric aluminum nitride (AlN) thin films via physical vapor deposition (PVD) techniques such as sputter deposition. The

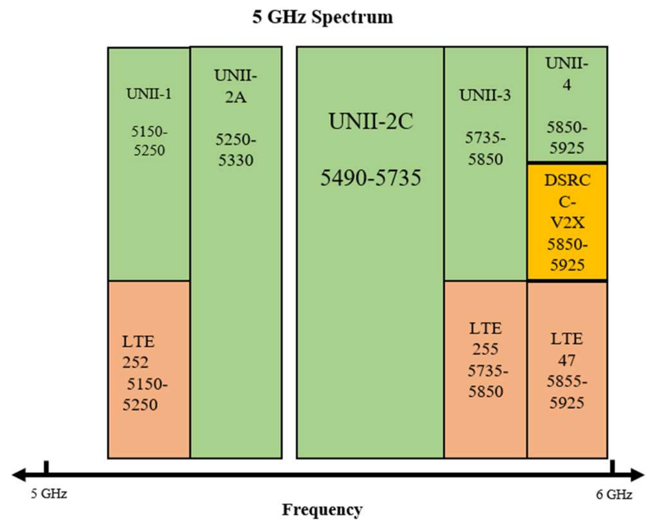

Fig. 1. 5 GHz unlicensed spectrum containing UNII bands.

resulting AlN thin films are poly-crystalline. Previous literature [6]-[10] demonstrating excellent results using PVD based AlN piezoelectric materials for higher frequency RF filter applications.

By contrast, a unique manufacturing flow for single crystal bulk acoustic wave (XBAW) resonators was recently reported demonstrating high power, wideband performance of 5.2 GHz filters for UNII 1+2A applications [11]. The XBAW™ wafer process offers flexibility to build filters from undoped and doped piezoelectric materials using either high purity CVD based films or PVD-based piezoelectric films.

In this work, the authors report fabricated XBAW RF filters with a center frequency of 5.66 GHz, -3 dB bandwidth of 452 MHz, a minimum insertion loss of 1.79 dB, out of band rejection greater than 50 dB and power handling performance (near the upper band edge) up to 32.5 dBm.

II. Device Technology

To achieve the UNII 2C+3 passband requirement of 360 MHz, doped AlN materials were developed and optimized for the XBAW filter process. A ladder-based RF filter was designed based on modeling results from previously fabricated resonators. The RF filter results from this work are compared to previously published micro filter results [2], [11]-[14] in Table I.

A piezoelectric layer consisting of doped AlN of 0.42um thickness (nominal target) was grown on a 150-mm diameter, silicon substrate. An 11-mask layer, two-sided wafer process, including sputter-deposited electrode metals and a silicon substrate thinning process yielded resonators with two air interfaces. Backside resonator electrode was routed to the topside of wafer using vias in the doped AlN thin film. A schematic diagram showing the structure of the fabricated XBAW resonators is shown in Fig. 2.

Table I.
Recent RF micro filter results in 4.5 – 6 GHz range

Ref.	Resonator Piezo Layer	Center Freq. (GHz)	Bandwidth (MHz)	Insertion Loss (dB)	Rejection (dB)
[2]	LiNb03	4.5	450	1.7	13
[12]	ZnO	5.2	130	1.6	15
[13]	AlN	5.2	151	2.8	38
[11]	AlN	5.2	205	<2	>50
[14]	AlN	5.25	160	<2	45
This work	Doped AlN	5.6	452	<2.3	50

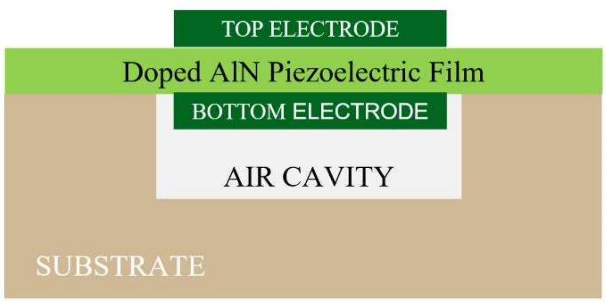

Fig 2. Cross-section of an XBAW resonator.

III. Resonator Results

A. Resonance and k^2_{eff} Extraction

The measured S-parameters of the 1-port resonator are collected on-wafer using 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. A plot of the magnitude and phase of the resulting Y-parameter for the resonator is shown in Figs. 3 and 4.

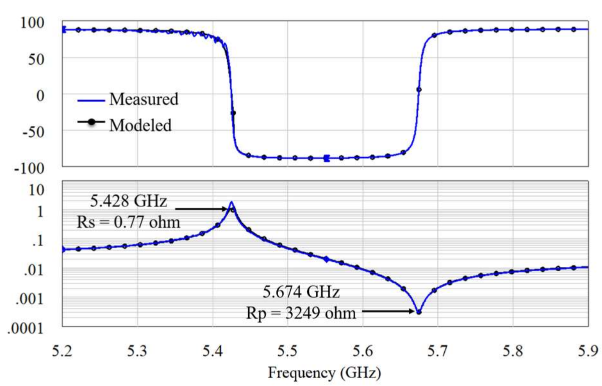

Fig 3. Narrowband comparison of measured data to mBVD model fit in both phase and magnitude.

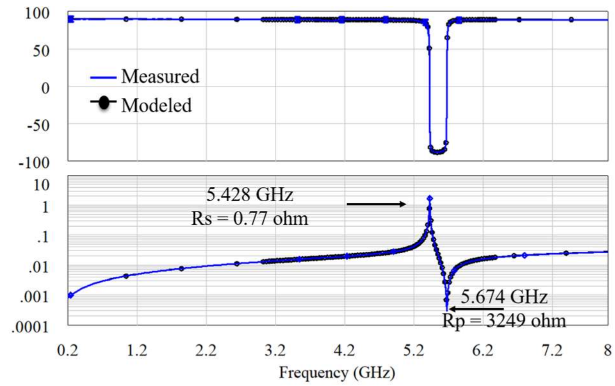

Fig 4. Wideband comparison of measured data to mBVD model fit in both phase and magnitude.

The measured and de-embedded data was fit to a modified Butterworth Van-Dyke (mBVD) model. The mBVD model parameters were obtained by simultaneously optimizing the fit to measured S and Y characteristics (Figs. 3 and 4) as well as the Bode Q-factor plot (Fig. 5). The resulting fit and mBVD model is shown in Fig. 6. The resonant frequency (f_s) and anti-resonant frequency (f_p) were extracted from the zero crossing of phase of the de-embedded resonator Y-parameters and determined to be 5.428 GHz and 5.674 GHz respectively. The calculated value of k^2_{eff} was 10.24%, using (1).

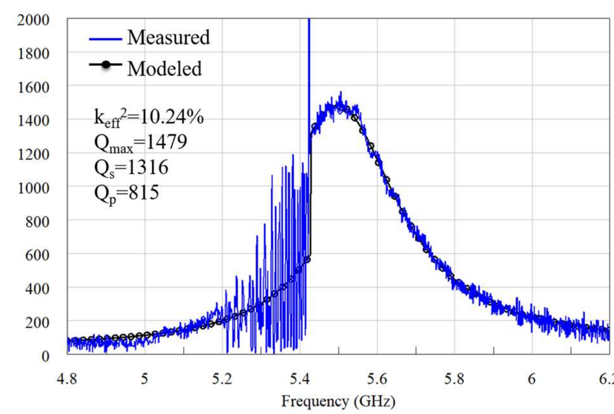

Fig 5. Bode plot showing Q-factor vs. frequency, for baseline and modified resonators, based on the mBVD model fit to measured data.

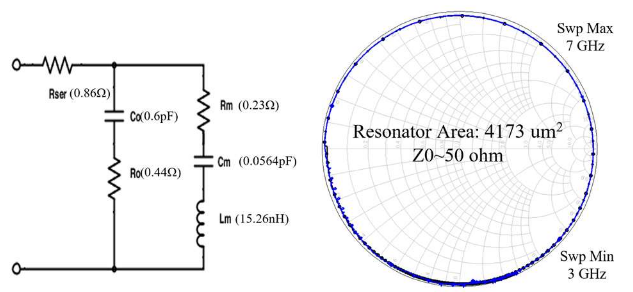

Fig 6. Measured S with overlay on a Smith Chart showing good agreement. Schematic and values of the mBVD model are included.

$$k_{eff}^2 = \frac{\pi^2}{4} \cdot \frac{f_1}{f_2} \cdot \frac{f_2 - f_1}{f_2} \quad (1)$$

B. Q-factor Characterization

The Bode plot of the de-embedded measured resonator is shown in Fig. 5 which is calculated using (2). The Q-factor obtained from the fitted mBVD model was evaluated using the method described in [15] and is shown in Fig. 5. Based on the Bode plot, Q_{fs} was 1316, Q_{fp} was 815 and Q_{max} was 1479. This translates to a resonator figure of merit of 151 at 5.5 GHz.

$$Q(\omega) = \omega \frac{d\phi}{d\omega} \frac{|S_{11}|}{1 - |S_{11}|^2} \quad (2)$$

IV. MEASURED FILTER RESULTS

A half-ladder network filter was designed in AWR Microwave Office using a calibrated modified Mason model of the doped AlN acoustic resonator. The design consists of 11 elements – 6 series and 5 shunt resonators – that constitute a classical ladder topology. Fig. 7 shows a 3D model of the measured filter die with package, where the die size on wafer is 0.557 mm^2.

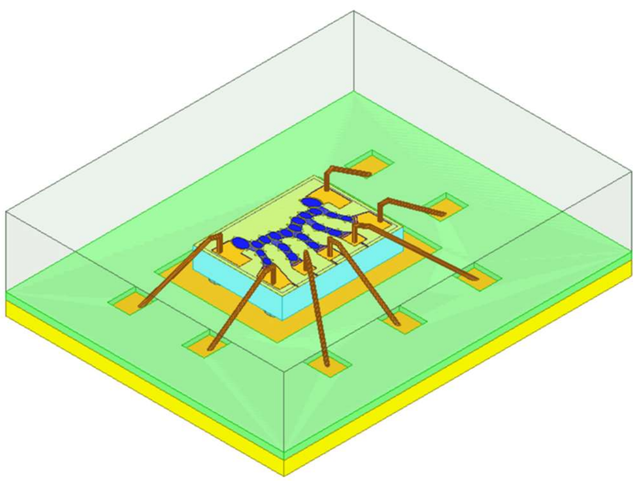

Fig 7. 3D model of the 5.66 GHz bandpass filter die with package.

A plot of the measured filter passband response is shown in Fig. 8, demonstrating a minimum IL of 1.79 dB, an average IL of 2.25 dB, center frequency of 5.66 GHz, and -3 dB bandwidth of 452 MHz. The passband skirt roll off is -0.5 dB/MHz on low frequency side and -1.1 dB/MHz on the high frequency side. Fig 8 shows out of band rejection greater than 50 dB in the UNII 1+2A band. A plot of the wide band filter performance (S21) is shown in Fig. 9, indicating high isolation above 10 GHz.

Peak power test has been performed with WCDMA signal at 5.825 GHz (10 MHz lower than upper band-edge). 12 randomly selected devices mounted on evaluation PCB boards were tested and damaged at the power levels between 31 dBm and 32.5 dBm.

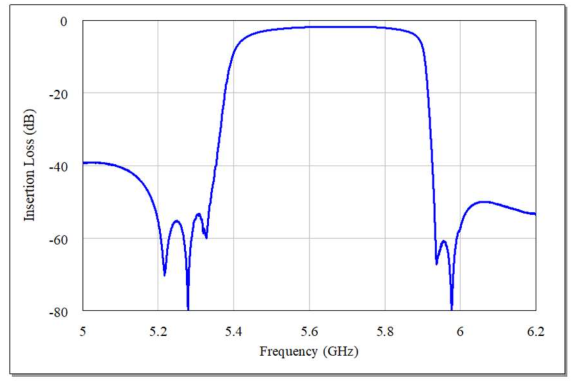

Fig 8. Measured narrow band S_{21} for the fabricated 5.66 GHz filter showing minimum insertion loss of 1.79 dB and -3 dB bandwidth of 452 MHz.

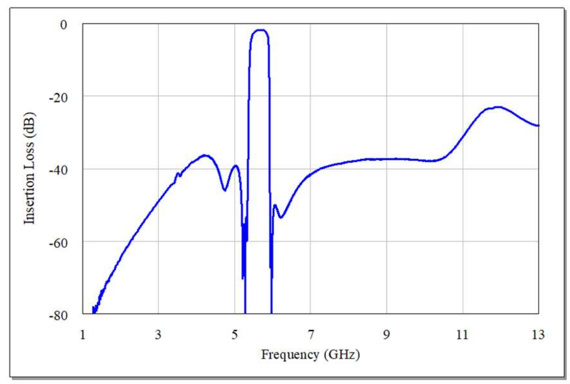

Fig 9. Measured wide band S_{21} for the fabricated 5.66 GHz filter showing minimum insertion loss of 1.79 dB and -3 dB bandwidth of 452 MHz.

V. CONCLUSION

XBAW filters operating at center frequency of 5.66 GHz, comprising of BAW resonators utilizing doped AlN piezoelectric films grown on silicon substrates are reported. The fabricated filters exhibited a -3dB bandwidth of 452 MHz (8% fractional bandwidth), a minimum insertion loss of 1.79 dB, an average insertion loss of 2.25 dB and out of band rejection greater than 50 dB in the UNII 1+2A band. Realized filter die sizes were 0.557 mm^2 which is less than a tenth of the size of resonant cavity filters that currently are used in WiFi routers. Resonators on the same wafer show an electro-mechanical coupling of 10.24% and maximum Q-factor of 1479. This is the first demonstration of doped AlN-on-Si on BAW resonator and filter technology at 5.66 GHz enabling small form factor with high power handling for high frequency Wi-Fi and UNII band infrastructure applications.

REFERENCES

[1] https://www.networkcomputing.com/wireless-infrastructure/channel-bonding-wifi-rules-and-regulations

[2] Y. Yang, R. Lu, L. Gao, and S. Gong, "4.5 GHz Lithium Niobate MEMS Filters With 10% Fractional Bandwidth for 5G Front-Ends", IEEE Journal of Micro Electro Mechanical Systems, June 2019.

[3] K. Hashimoto, "RF Bulk Acoustic Wave Filters for Communications" Artech House., pp161-171, 2009

[4] R. Ruby, "Current Status, Future Growth for Filters used in Cell Phones, Proc. Intl Symp. on Acoustic Devices, Chiba, Japan, 2015, pp13-17.

[5] R. Aigner, G. Fattinger, A. Tajic, A. Volatier, F. Dumont, P. Stokes, M. AlJoumayly, "The Edge of Tomorrow in BAW: Innovate, Ramp, Repeat., Proc. Intl Symp. on Acoustic Devices, Chiba, Japan, 2015, pp7-12.

[6] K.M. Lakin, J.R. Belsick, J.P. McDonald, K.T. McCarron, C.W. Andrus "Thin Film Resonators and Filters, in Micr. Symp. Digest, IEEE IMS., pp1487-1490, 2002.

[7] H.P. Loebl, C. Metzmacher, D.N. Peligrad, "Solidly mounted bulk acoustic wave filters for the GHz frequency range, in Proc. IEEE Ultrason. Symp., pp919-923, 2002.

[8] T. Nishihara, T. Yokoyama, T. Miyashita, and Y. Satoh, "High performance and miniature thin film bulk acoustic wave filters for 5 GHz, Proc. IEEE Ultrason. Symp., pp969-972, 2002.

[9] R. Lanz, P. Muralt, "Solidly mounted BAW filters for 8 GHz based on AlN thin films, Proc. IEEE Ultrason. Symp., pp178-181, 2003.

[10] G.G. Fattinger, J. Kaitila, R. Aigner, W. Nessler "Thin Film Bulk Acoustic Wave Devices for Applications at 5.2 GHz," Proc. IEEE Ultrasonics Symposium, p174, 2003

[11] R. Vetury, M.D. Hodge J.B. Shealy, "High Power, Wideband Single Crystal XBAW Technology for sub-6 GHz Micro RF Filter Applications" 2018 IEEE International Ultrasonics Symposium (IUS), Oct 2018.

[12] R. Kubo, H. Fujii, H. Kawamura, M. Takeuchi, K. Inoue, Y. Yoshino, T. Makino, S. Arai, "Fabrication of 5 GHz Band Film Bulk Acoustic Wave Resonators Using ZnO Thin Film" 2003 IEEE International Ultrasonics Symposium (IUS), pp 166-169, 2003.

[13] M.D. Hodge, R. Vetury, S.R. Gibb, M. Winters, P. Pinal, M.A. McLain, Y. Shen, D.H. Kim, J. Jech, K. Fallon, R. Houlden, D.M. Aichele and J.B. Shealy., "High Rejection UNII 5.2 GHz Wideband Bulk Acoustic Wave Filters Using Undoped Single Crystal AlN-on-SiC Resonators", IEEE IEDM, pp625-628, December 2017.

[14] R. Aigner, G. Fattinger, M. Schaefer, K. Karnati, R. Rothemund, and F. Dumont, "BAW Filters for 5G Bands", IEEE IEDM, pp332-335, December 2018.

[15] R. Ruby, R. Parker, D. Feld, "Method of Extracting Unloaded Q Applied Across Different Resonator Technologies, Proc. of IEEE Ultrason. Symp., pp1815-1818, 2008