18 GHz Solidly Mounted Resonator in Scandium Aluminum Nitride on $SiO₂/Ta₂O₅ Bragg Reflection$

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*Abstract***—This work reports an acoustic solidly mounted resonator (SMR) at 18.64 GHz, among the highest operating frequencies reported. The device is built in scandium aluminum nitride (ScAlN) on top of silicon dioxide (SiO2) and tantalum pentoxide (Ta2O5) Bragg reflectors on silicon (Si) wafer. The stack is analyzed with X-ray reflectivity (XRR) and high-resolution Xray diffraction (HRXRD). The resonator shows a coupling** coefficient (k^2) of 2.0%, high series quality factor (Q_s) of 156, shunt quality factor (Q_p) of 142, and maximum Bode quality factor (Q_{max}) **of 210. The third-order harmonics at 59.64 GHz is also observed** with k^2 around 0.6% and Q around 40. Upon further development, **the reported acoustic resonator platform can enable various frontend signal-processing functions, e.g., filters and oscillators, at future frequency range 3 (FR3) bands.**

*Index Terms***—acoustic resonators, piezoelectric devices, solidly mounted resonators, thin-film devices**

I. INTRODUCTION

PIEZOELECTRIC resonators have been used for radio frequency (RF) front-end applications, e.g., filters and frequency (RF) front-end applications, e.g., filters and oscillators . Piezoelectric devices transduce electrical signals into mechanical vibrations and process within the acoustic domain [1]. The main differentiator of acoustics over electromagnetic (EM) technology is that it provides four orders of magnitude smaller sizes along with better frequency selectivity [2]–[4]. Thus, thin-film bulk acoustic wave resonators (FBAR) and surface acoustic wave (SAW) devices are the dominant front-end filtering solutions [5]–[8].

More recently, the pursuit for faster data rate is driving wireless communication systems into higher frequency bands, e.g., frequency range 3 (FR3, 7.125 GHz to 24.25 GHz) and millimeter-wave bands (above 30 GHz) [9], [10]. The frequency scaling causes new challenges in acoustics as device performance degrades at higher frequencies [11], [12]. The main issue is that the acoustic wavelengths fall below 500 nm. One method is to use ultra-thin films or fine feature size electrodes [13]–[19], but the mechanical and electrical loss will be high, marked by reduced quality factor (*Q*). Alternatively, overmoding with higher-order tones in a larger cavity is

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Fig. 1 Device schematics in (a) cross-sectional view of a unit cell, and (b) top view of the electrodes and reflectors.

feasible, this approach has been demonstrated in single and periodically poled piezoelectric (P3F) devices [20]–[25]. However, this comes with fabrication complexities in P3F stacks, whereas single film suffers from low electromechanical coupling (k^2) due to charge cancellation.

Lately, the development of thin-film piezoelectric material, design, and fabrication has enabled a series of acoustic resonators beyond 18 GHz, mostly using suspended thin-film lithium niobate (LiNbO₃) [26]–[29] and scandium aluminum nitride/aluminum nitride (ScAlN/AlN) [21], [30]–[32]. Despite the remarkable advance of the state of the art, one issue remains for the power handling, which is intrinsically weak due to their structure with suspended membranes.

One promising platform is solidly mounted resonators (SMRs) [33]–[35] . In SMRs, the piezoelectric resonant cavity is above an acoustic quarter-wavelength Bragg reflector, consisting of alternating low and high acoustic impedance layers, deposited on the top of a carrier wafer [Fig. 1(a)]. The advantages of SMRs include intrinsically stable mechanical structure and high power handling [36]. However, scaling high *Q* and *k ²* SMRs beyond 10 GHz is not trivial, as the reflector also needs to be scaled, causing additional challenges, both on the design and microfabrication end. So far, SMRs are mostly

Fig. 2 Simulated acoustic mode shapes in (a) displacement, (b) T_x , and (c) T_z .

limited to sub 10 GHz [37]–[43].

In this work, we report an SMR at 18.64 GHz using ScAlN on top of silicon dioxide (SiO₂) and tantalum pentoxide (Ta₂O₅) Bragg reflectors on silicon (Si) wafer. The resonator shows k^2 of 2.0%, high series quality factor (Q_s) of 156, shunt quality factor (Q_p) of 142, and maximum Bode quality factor (Q_{max}) of 210. The third-order harmonics at 59.64 GHz is also observed with k^2 around 0.6% and Q around 40. The device also features a temperature coefficient of frequency (TCF) of −47.6 ppm/K for series resonance and −60.6 ppm/K for shunt resonance.

Upon further development, the reported acoustic resonator platform can enable various front-end signal-processing functions, e.g., filters and oscillators, at FR3 and mmWave bands.

II. DESIGN AND SIMULATION

The stack of the proposed SMR is shown in Fig. 1 (a), with the key dimensions listed in Table I. The stack includes 40 nm aluminum (Al) electrode on the top of 68 nm $Sc_{0,3}Al_{0,7}N$, deposited on SiO2/Ta2O⁵ Bragg reflector pairs on Si carrier wafer. The Bragg reflector consists of 8.5 pairs (17 layers in total) of thin films, with alternating $75 \text{ nm } \text{SiO}_2$ and 65 nm Ta2O5. The transducer design follows a conventional interdigitated electrodes (IDT) design with shorted metallic electrodes on the side [Fig. 1 (b)] [44]. The cell length (Λ) is chosen as 434 nm to excite a resonance around 18 GHz for the given $Sc_{0.3}Al_{0.7}N$ thickness. The electrode width is 108 nm and is based on a fabrication process previously validated in [45]. The period of the lateral IDT is 432 nm, and the electrode width is 108 nm. The resonator layout includes 50 pairs of IDTs and 15 pairs of reflectors on each side.

In operation, the alternating electric field between IDT excites a confined longitudinal mode in ScAlN [displacement mode shape in Fig. 2 (a)]. The piezoelectric transduction is achieved from the thickness-direction electric field component, coupled into the lateral stress component $[T_x \text{ in Fig. 2 (b)}]$ and thickness stress component $[T_z \text{ in Fig. 2 (c)],$ via piezoelectric coefficients *e³¹* and *e33*, respectively. The piezoelectric coefficients follow that in [46]. In the thickness direction, the acoustic energy is confined, as the Bragg reflector transforms the impedance of the substrate to a minimal value comparable to air, effectively providing a free boundary condition at the bottom of ScAlN, supporting bulk acoustic modes on the top of

Fig. 3 Simulated frequency domain admittance in (a) magnitude and (b) phase.

Table II. Bragg Reflector Material Parameters in FEA

Sym.	Parameter	SiO ₂	Ta ₂ O ₅
	Density	2200 kg/m ³	6850 kg/m ³
	Young's Modulus	70 GPa	162 GPa
	Poisson Ratio	0.17	0.43
	Acoustic Impedance	12.4 Mkg/(m^2 ·s)	33.3 Mkg/(m^2 -s)
	Acoustic Velocity	5640 m/s	4860 m/s

the reflectors.

The stack is optimized via three-dimensional (3D) eigenmode analysis of a unit cell with one lateral wavelength in COMSOL finite element analysis (FEA). Periodic boundary conditions are applied on the sides. A perfectly matched layer (PML) is included at the bottom to represent the carrier Si wafer. The parameters of the Bragg reflector are listed in Table II, showing SiO_2 and Ta_2O_5 as low and high acoustic impedance layers, respectively. The key material properties are listed in Table II [38]. The acoustic impedance for longitudinal waves are 12.4 Mkg/(m^2 ·s) and 33.3 Mkg/(m^2 ·s) for SiO₂ and Ta₂O₅, respectively. The expected fractional bandwidth (FBW) for the Bragg reflection is [47] calculated to be:

$$
FBW = \frac{4}{\pi} \cdot \arcsin\left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right) \tag{1}
$$

which yields FBW of 60.7%, indicating wideband function.

The Bragg reflector thickness is initially selected based on the longitudinal acoustic quarter wavelengths at 18 GHz, then optimized by parametrically sweeping the stack thickness, toward ensuring the eigenfrequency is purely real, indicating no energy loss into the substrate, modeled by the PML. The ScAlN thickness, Al thickness, and lateral wavelengths are selected with consideration of high k^2 at 18 GHz and also microfabrication limits. The mode shapes in Fig. 2 indicate that the vibration is well confined, and its amplitude exponentially decays into the Bragg reflector, validating the design.

The frequency domain simulated admittance of SMR is plotted in Fig. 3 (a) and (b) in magnitude and phase, respectively. The extracted k^2 is 2.2%, obtained via Butterworth-Van Dyke (BVD) fitting, which is equivalent to $k^2 = \pi^2/8 \cdot (f_p^2/f_s^2 - 1)$ for this case, without EM effects, e.g., routing inductance and resistance [20]. Mechanical *Q* is set to 200 based on that reported in recent ScAlN works around 18 GHz [48]. The results show great promise for SMR at 18 GHz and beyond. Future enhancement of k^2 will require the implementation of a bottom electrode layer between the ScAlN and Bragg reflector, introducing additional fabrication complexity. Here, the feasibility of higher frequency SMR is showcased.

Fig. 4 (a) Measured XRR scan against layered model data, (b) Cross-section SEM of the stack and (c) Diffraction scan with detected material peaks (d) XRD rocking curve and FWHM estimation.

III. FABRICATION

The fabrication starts with depositing the 8.5 pairs of $SiO₂/Ta₂O₅$ Bragg reflectors on the top of the Si wafer. The large number of pairs is chosen to validate the consistency and repeatability of the process. The deposition is done with a HELIOS 800 sputter coater by Buhler Leybold Optics, equipped with three magnetron sputter stations for physical vapor deposition (PVD), a plasma beam source (PBS) as an ionassist source, two electrical heaters, and an optical monitoring system (OMS) for in-situ thickness monitoring. The alternating $SiO₂$ and Ta₂O₅ layers in the Bragg reflector stack were sputtered through the PVD stations using a plasma-assisted reactive magnetron sputtering (PARMS) [49] approach on Siwafers. In PARMS, the PVD stations are equipped with metallic targets and operate with a mixed gas $(Ar \text{ and } O_2)$, while the process is controlled using lambda probes. The lambda probes help stabilize the process at an ideal working point where it operates at the edge of the oxidic limit without oxidizing the target surface, hence ensuring perfectly stoichiometric oxide layers with optimized deposition rates. The process is supported by the PBS, which provides oxygen radicals for better O_2 intercalation and reduces absorption in the films. The thickness was monitored in-situ by OMS in transmission with self-error compensation of optical thicknesses to achieve accurate physical thickness of the stack [50]. The coatings were performed at a deposition temperature of 150 \degree C.

Next, a 68 nm thin film of $Sc_{0.3}Al_{0.7}N$ was deposited onto the top $SiO₂$ layer using an Evatec Clusterline-200 magnetron sputtering system. A 12-inch $Sc_{0,3}Al_{0,7}N$ casted target has been utilized for this process. During the deposition, the target and substrate were positioned 20 mm apart. A steady flow of nitrogen gas (N_2) at a rate of 20 sccm was maintained, while the

Fig. 5 (a) Optical and (b) SEM images of the fabricated resonator.

substrate was kept at a temperature of 400 °C. No argon was introduced to minimize roughness and abnormally oriented grains (AOG) formation on the film surface. 5 kW of pulsed-DC was applied to the target at 100 kHz with 88% on duty cycle for 103 seconds (0.66 nm/s deposition rate). Afterward, the top electrodes are patterned with electron-beam lithography, 40 nm Al IDT evaporation, and lift-off process. Finally, the busline regions are thickened by 300 nm evaporated Al.

The X-ray reflectivity (XRR) and high-resolution X-ray diffraction (HRXRD) measurements were performed on a D1 (Bruker/Jordan Valley) diffractometer using Cu Kα1 radiation with an incident beam optic to produce a parallel beam and a Si (220) monochromator. Specular XRR scans were performed using a 0.01 deg scattered beam slit and the HRXRD measurements used a 0.3 deg scattered beam slit. The XRR scans were simulated using REFS, a modeling program. The match between the experiment and the simulation confirms that the layer thickness is highly repeatable and uniform. The Scandium mole fraction in the $Al_{1-x}Sc_{x}N$ alloy was determined through a combination of a symmetric $2θ$ -ω scan $[(0002)$ and (0004) reflections] and an asymmetric 2θ-ω scan across the (10- 13) reflection to measure the a and c lattice parameters. These were then matched to the lattice parameters in reference [51]. A limited area pole figure around the (10-13) reflection was also produced. In this case, a detector aperture of 1.7 deg was utilized. A scanning electron microscopy (SEM) image was produced after focused ion beam cutting to reveal the layer thicknesses.

Fig. 4 (a) shows the specular XRR scan and a simulated scan that superimposes the experimental data. For the simulated scan, the modeled structure included eight identical layers of $Ta₂O₅$ (thickness = 64.3 nm) and nine layers of $SiO₂$ (thickness 74.8 nm) as well as an AlScN layer approximately 81.6 nm thick. The fringe periodicity determines the period thickness, the equivalent narrowness of the peaks at low and higher angles indicates there is little thickness drift or dispersion and the relative amplitude of the peaks is primarily determined by the thickness ratio of the two layers. The $Al_{1-x}Sc_{x}N$ composition predicted from the XRR simulation is approximately $X(Sc) =$ 0.32 but the XRR measurement is not very sensitive to this composition. The comparison of measured and expected stack parameters are listed in Table III.

Fig. 4 (b) is the SEM image of the cross-section of layers. The Ta_2O_5 layers are lightest here, the SiO_2 layers darker, and the AlScN layer is the darkest of all. The uniform thickness of the layers and the number of layers modeled in the XRR result is consistent with the SEM image. Fig. 4 (c) shows a diffraction scan over a 2θ range from 10-90 deg. In addition to the (004) Si substrate peak, the peaks at 36.2 deg and 76.8 deg correspond to the (0002) and (0004) AlScN peaks,

Fig. 6 Measured acoustic resonator admittance and fitting results for zoom-in (a) magnitude, (b) phase, and wideband (c) amplitude, and (d) phase.

		$C_{m1} = 8/\pi^2 \cdot C_0 k_1^2$
L _s	Static Capacitance	$R_{m1} = \pi^2/8 \cdot 1/(\omega_{s1} C_0 k_1^2 Q_1)$
Routing Inductance & Resistance	R_{m1} L_{m1} C_{m1}	$L_{m1} = \pi^2/8 \cdot 1/(\omega_{s1}^2 C_0 k_1^2)$
		$C_{m3} = 8/\pi^2 \cdot C_0 k_3^2$
Motional BVD Components	C_{m3} L_{m3} $\n m3$	$R_{m3} = \pi^2/8 \cdot 1/(\omega_{s3} C_0 k_3^2 Q_3)$
		$L_{m3} = \pi^2/8 \cdot 1/(\omega_{s3}^2 C_0 k_3^2)$

Fig. 7 Modified mmWave multi-branch BVD model for parameter extraction.

Table IV. Extracted Device Parameters

Sym.	Parameter	Value	Sym.	Parameter	Value
f_{s1}	Resonance	18.64 GHz	$f_{\rm s3}$	Harmonics Resonance	59.64 GHz
k_1^2	Coupling	2.0%	$k_3{}^2$	Harmonics Coupling	0.6%
Q	Fit Q	210	Q_3	Harmonics Fit Q	40
R_{s}	Series Resistance	3.5Ω	Ls	Series Inductance	0.04 nH
C ₀	Static Capacitance	157 fF			

respectively. No other AlN peaks are observed, indicating that the AlN is highly oriented. A pole figure near the (10-13) expected reflection shows weak six-fold ordering. The composition of the Al_{1-x}Sc_xN was determined to be X(Sc) ~ 0.31-0.32. Fig 4(d) shows the measured rocking curves of the thin film, with a full width at half maximum (FWHM) of 3.25, comparable to those reported in recent works [30], [31].

Fig. 5 (a) and (b) show optical and scanning electron microscope (SEM) images of the fabricated resonators, respectively. The key dimensions are listed in Table I.

IV. MEASUREMENT

The resonators are first measured using a Keysight vector network analyzer (VNA) in air at −15 dBm power level. Both zoom-in and wideband admittance and phase of the resonators are plotted in Fig. 6 (a)-(d), fitted with the mmWave MBVD circuit model [26] in Fig 7. The parameters for fitting are listed in Table IV. Unlike conventional MBVD models, the inductive effects from routing inductance *L^s* are included together with *Rs*. Such *L^s* and static capacitance *C⁰* forms an EM resonance at

Fig. 9 Extracted TCF of the (a) series and (b) shunt resonances at 18 GHz.

higher frequencies, indicated by the inductive phase beyond 55 GHz. Two motional branches are included for the 18 GHz and 59 GHz tones, respectively, with corresponding motional elements L_m , C_m , and R_m .

The resonance at 18.64 GHz show shows k^2 of 2.0%, high series quality factor Q_s of 156 and shunt quality factor Q_p of 142. The harmonics at 59.64 GHz is also observed with k^2 around 0.6% and extracted *Q* around 40. The Bode *Q* of the first tone is plotted in Fig. 8, showing maximum Bode quality factor *Qmax* of 210 [52].

Next, TCF is measured with a Lakeshore cryogenic probe station TTPX, where the temperature varies between 300 K and 360 K. The resonances drift to lower frequencies at elevated temperature, due to negative TCF. The series and shunt TCF, defined by the frequencies where the admittance is pure real, are measured and fitted in Fig. 9 (a) and (b), respectively. The TCF is −47.6 ppm/K for series resonance and −60.6 ppm/K for shunt resonance. The value is higher than that in reported suspended ScAlN/AlN resonators [53], likely impacted by $Ta₂O₅$ and Al in the stack, and will be studied in future works.

Compared with SoA (Table V) of reported SMR, this work presents noticeable frequency scaling along with reasonably good resonator performance metrics, especially the high *Q* above 200 at 18 GHz. The modest k^2 is a combination of using lateral excitation for the device, which has limited available coupling, in addition to having energy leaking into the bragg reflector as seen in Fig 2 (c). It could be further improved using thickness excitation with a bottom electrode, in a slight tradeoff with fabrication complexity.

It is expected that the resonator would have better power handling than a similar IDT laterally excited device on a suspended film. Future studies will focus on reliable large signal analysis to measure power handling capabilities [54] .

V. CONCLUSION

In this work, we report an SMR at 18.64 GHz using ScAlN on top of $SiO₂/Ta₂O₅$ Bragg reflectors on Si wafer. The resonator shows k^2 of 2.0%, high series quality factor Q_s of 156, shunt quality factor Q_p of 142, and maximum Bode quality factor *Qmax* of 210. The device surpasses SoA and highlights the possibility of scaling SMRs toward various front-end signalprocessing functions, e.g., filters and oscillators, at FR3 and mmWave bands.

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