# HIGH PERFORMANCE BULK MODE GALLIUM NITRIDE RESONATORS AND FILTERS

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## ABSTRACT

In this paper, measurements and characterization results of several micromechanical bulk-mode resonators and filters fabricated from single crystalline gallium nitride are presented. A 167.6 MHz length-extensional mode resonator is demonstrated that exhibits an unloaded quality factor of 1370 and motional impedance of 485 Ω at atmospheric pressure and 300 K. The $f \times Q$ values of the resonators presented in this work measured under ambient conditions are significantly higher than prior work and prove that GaN is a suitable material as a micromechanical resonating element for high-power applications. The relevant material properties of GaN are also characterized.

## KEYWORDS

Gallium nitride, contour mode resonators, bulk mode filters, effective piezoelectric coupling coefficient.

## INTRODUCTION

Gallium nitride (GaN) is a wide bandgap semiconductor material and is fast becoming the most popular material after silicon in the semiconductor industry. The prime movers behind this trend are LEDs, photodiodes and microwave electronics. Recent areas of research also include spintronics and nanowire transistors, which leverage some of the unique properties of GaN. GaN has electron mobility comparable to silicon, but with a bandgap that is three times wider, making it an excellent candidate for high power application and high temperature operation. The ability to form thin AlGaN/GaN interfaces which exhibit the 2D electron gas (2DEG) phenomenon leads to high electron mobility transistors (HEMTs), which are very useful for high-frequency and high-power operation [1].

Another interesting direction for GaN research which is largely unexplored can be GaN-based micromechanical devices, or GaN MEMS. GaN has a high acoustic velocity (comparable to silicon) and large piezoelectric coefficients (comparable to that of aluminum nitride (AlN)) making it a strong candidate for MEMS resonators. There has been some prior work on GaN FBARs [2], or flexural beam resonators integrated with HEMTs [3] showing reasonable performance but with quality factors ($Q$s) much lower than the intrinsic limit of GaN. GaN surface acoustic wave (SAW) devices have also been explored to some extent [4]. However, a systematic investigation is required to fully understand the mechanical properties of GaN as a micromechanical resonating element and exploit its unique properties. Fundamental design principles can be derived from the extensive research on AlN resonators and filters. Integration of GaN MEMS and HEMTs can broadly follow strategies successfully used in the integration of silicon MEMS with CMOS electronics. In this paper, fabrication, design, and characterization of bulk acoustic wave GaN-based micromechanical resonators and filter are presented. Important material properties of GaN such as longitudinal acoustic velocity and the effective piezoelectric coupling coefficient are experimentally characterized.

## FABRICATION AND DESIGN

### Fabrication Process

The GaN thin film was epitaxially grown on 100 mm silicon <111> substrates, using a custom-built cold-wall rotating disc metal-organic chemical vapor deposition (MOCVD) reactor. The growth temperature was 1020 ˚C. The full epitaxial stack consists of an AlN nucleation layer, followed by two AlGaN layers, which complete the transition layer. A 1.2 µm thick GaN film was subsequently grown on top of the transition layer. The transition layer is required to alleviate the problem of film stress caused because of the lattice mismatch between the silicon substrate and the GaN epi-layer.

A 50 nm PECVD silicon nitride layer was deposited to reduce electrical feed-through as GaN is un-intentionally doped. GaN and silicon nitride layers were then plasma etched using $Cl_2/BCl_3$ chemistry to define the resonator boundary. Top electrodes of 10 nm Ti and 100 nm of Au were deposited and patterned using the lift-off process. A 400 nm thick gold layer was deposited on the signal and ground pads to reduce the probe contact resistance. Devices were released using selective DRIE etching of silicon from the backside. Finally, the bottom electrode (10 nm Ti/100 nm Au) was sputter deposited from the backside. Fig. 1 shows a SEM view of a fabricated GaN resonator.

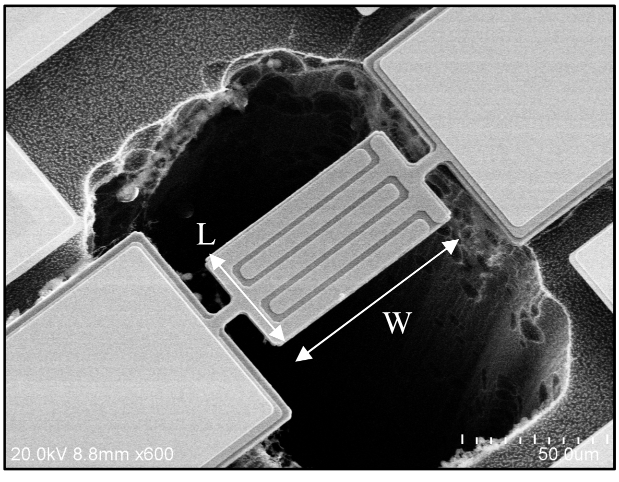
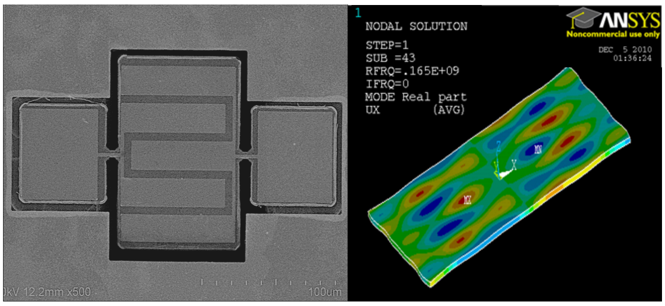


*Figure 1: A SEM view of a fabricated GaN resonator.*

### Design and Finite Element Analysis

Several bulk mode resonators and filters working at different frequencies from tens of megahertz to a few gigahertz were designed and fabricated. The length extensional mode was chosen as the primary mode of resonance as the frequency of this mode depends solely on the lithographic dimensions of the resonating material and the electrode configurations, and not on the film thickness. Resonators are designed in two-port configurations using interdigitated transducer (IDT) top electrodes. Physical dimensions of the resonators range from 40 µm to 120 µm, with the width independently varying in the same range. Fig. 2(a) shows a SEM image of a GaN resonator that is 120 µm long and 80 µm wide. The resonator is tethered at the midpoint along the length with 10 µm long anchors. The top electrode has a total of five fingers and is operated at its fifth length extensional mode. Fig. 2(b) shows the mode shape of the resonator simulated using ANSYS. This specific design, called Device A, is fully characterized in this work.

For filters, thickness mode resonance was chosen to achieve higher frequencies without being constrained by the minimum feature size attainable using optical lithography. High-frequency GaN thickness-mode filters have been investigated by our group previously [5]. In the current work, thickness-mode resonators and filters have been monolithically integrated on the same substrate as the length-extensional mode resonators, which allows for versatile design possibilities in a GaN-based integrated electromechanical system.



(a) (b)

*Figure 2:(a) A SEM image of a 120 µm × 80 µm resonator with five IDT fingers (Device A). The anchor width is 10 µm. (b) ANSYS FEA modal analysis of the resonator, showing the fifth-order length-extensional mode at 164.56 MHz.*

## MEASUREMENT RESULTS

The RF measurements were carried out using a Suss Microtek PM5 Probe station, an Agilent N5241A PNA, and GSG ACP40 probes from Cascasde Microtech. Short-Open-Load-Through (SOLT) calibration is performed prior to measurements and no de-embedding is performed. All measured data are acquired with 50 Ω termination impedance.

Fig.3 shows the measured transmission response of the two-port GaN resonator shown in Fig. 2 (Device A). This device exhibit a measured *Q* of 1173 at 167.26 MHz when measured at atmospheric pressure and room temperature. The unloaded *Q* of this resonator measured at 3 µTorr and at 78K is 1886 (Fig.4). The measured frequency of the resonators matches well with the simulated response shown in Fig. 2(b).

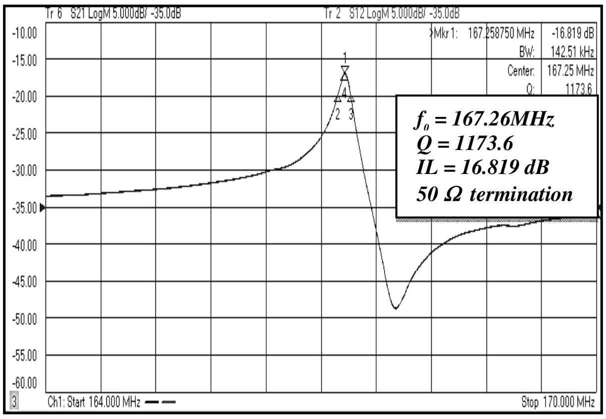


*Figure 3: Measured $S_{21}$ of Device A (shown in Fig. 2(a)) at 300K and atmospheric pressure. The resonant frequency is 167.26 MHz with an insertion loss of 16.8 dB and Q of 1173. The unloaded Q is 1370.*

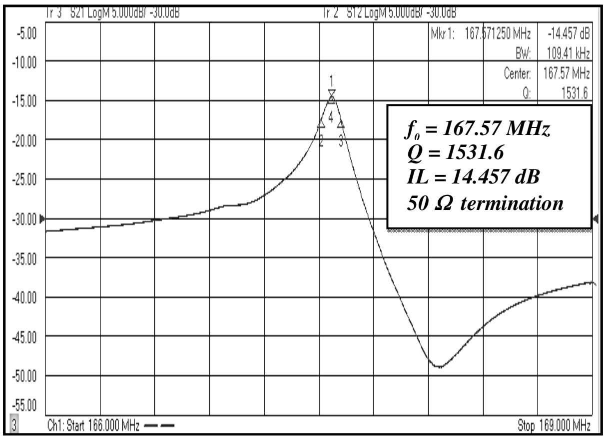


*Figure 4: Measured $S_{21}$ of Device A at 78K and 3µTorr. The resonant frequency is 167.57 MHz with an insertion loss of 14.457 dB and Q of 1532. The unloaded Q is 1886.*

Fig.5 shows the response of a thickness-mode filter fabricated on the same die. The frequency of this mode is 3.66 GHz with an insertion loss of 4 dB and bandwidth of 48 MHz.

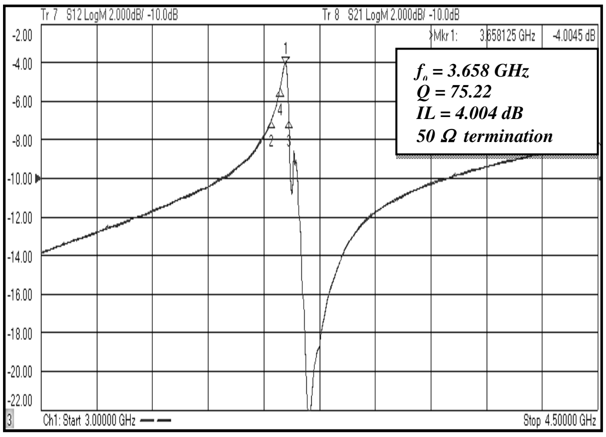


*Figure 5: $S_{21}$ parameters for a thickness-mode filter. The insertion loss is 4 dB at 3.66 GHz.*

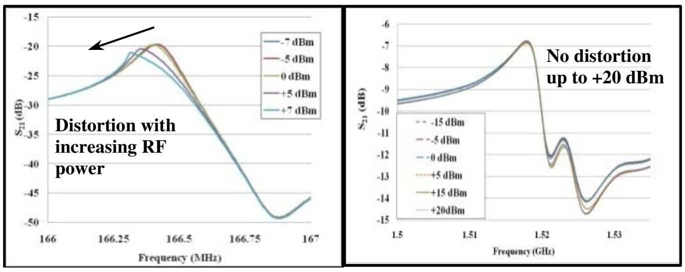
Table 1 presents measured characteristics of a number of devices, indicating their dimensions and order of resonance. The theoretical frequency is an estimate, based on published values for material properties of GaN [6], and not considering the loading effect of electrodes or film stress.

*Table 1**:** Measured parameters of the fabricated resonators.*

| # | Length (μm) | Width (μm) | Order | Analytical Frequency (MHz) | Measured Frequency (MHz) | Measured $Q$ |
|---|---|---|---|---|---|---|
| A | 120 | 80 | 5 | 163.76 | 167.25 | 1174 |
| B | 60 | 80 | 1 | 65.50 | 60.11 | 1968 |
| C | 60 | 80 | 5 | 327.52 | 306.95 | 1056 |
| D | 40 | 80 | 5 | 491.29 | 468.77 | 1714 |
| E | 40 | 80 | 5 | 491.29 | 465.43 | 1618 |
| F | 40 | 80 | 5 | 491.29 | 465.60 | 1130 |

## Power Handling

The power handling of the length-extensional mode resonators is measured in the range of -7 dBm to +7 dBm (Fig.6 (a)). Distortion is seen at input RF power of +5 dBm and above. However, prior results obtained by our group [5] for thickness-mode GaN filters with a clamped membrane anchor design indicate that GaN devices can handle much higher amounts of RF power without distortion (Fig.6 (b)). The distortion can be attributed to the fact that the length-extensional mode resonators are supported by slender GaN tethers with a cross section of only 5 μm × 1.2 μm. The power limit of +5 dBm is thus not a fundamental limit for GaN and the power handling performance can be improved using an optimum design or using GaN-on-Si configuration for the length-extensional mode resonators



(a) (b)

*Figure 6: (a) Distortion is seen at high power levels in the length-extensional mode resonators with thin anchors; (b) in contrast, clamped membrane type thickness mode filters show no distortion up to +20 dBm [5].*

## CHARACTERIZATION

### Material properties

Based on the measured values for resonant frequencies and assuming a standard value of 6150 kg/m$^3$ for the density of GaN [6], we can determine the longitudinal acoustic velocity to be approximately 7413 m/s with an effective Young's modulus of 337 GPa, which agree well with theoretical values. The acoustic velocity of GaN is very close to that of silicon (8400 m/s), which can be advantageous for GaN-on-Si resonator configurations.

Investigations into the piezoelectric coupling coefficient of un-doped or high-resistivity GaN have consistently yielded values close to ~1.9% [7, 8]. The highest value of $k_{eff}^2$ in this work is 0.83%, implying that there is still room for improving the performance of GaN resonators and filters. Table 2 lists the extracted $k_{eff}^2$ values and acoustic velocities for the measured resonators, along with a comparison with values from literature.

*Table 2: Extracted material properties of the resonators.*

| # | Measured Frequency (MHz) | Effective Acoustic Velocity (m/s) | Effective Young's Modulus (GPa) | $k_{eff}^2$ (%) |
|---|---|---|---|---|
| A | 167.25 | 7693.5 | 358.10 | 0.829 |
| B | 60.11 | 7213.56 | 320.01 | 0.586 |
| C | 306.95 | 7366.80 | 333.75 | 0.619 |
| D | 468.77 | 7500.40 | 345.97 | 0.541 |
| E | 465.43 | 7447.02 | 341.06 | 0.587 |
| F | 465.60 | 7449.66 | 341.30 | 0.762 |
|  | Un-doped GaN [7] |  |  | 1.9 |
|  | Theoretical model[8] |  |  | 1.9 |

## Temperature Coefficient of Frequency

The temperature coefficient of frequency (TCF) of resonators was extracted from their frequency response measured over a temperature range of -40˚C to +80˚C. Fig.7 shows the trend for Device A. The TCF was found to be -17.7 ppm/˚C, which is comparable to that of silicon. This makes it possible to use temperature compensation techniques similar to those used in silicon resonators.

As shown in Fig. 7, the variation of unloaded $Q$ in the same temperature range is proportional to $T^{-0.9}$, which indicates that the resonator is operating in the Akhieser regime of phonon-phonon dissipation [9]. The $f \times Q$ of measured devices is in the range of $3 \times 10^{11}$, the highest reported for GaN resonators but lower than the theoretical limit for bulk GaN in the Akhieser regime (Fig. 8).

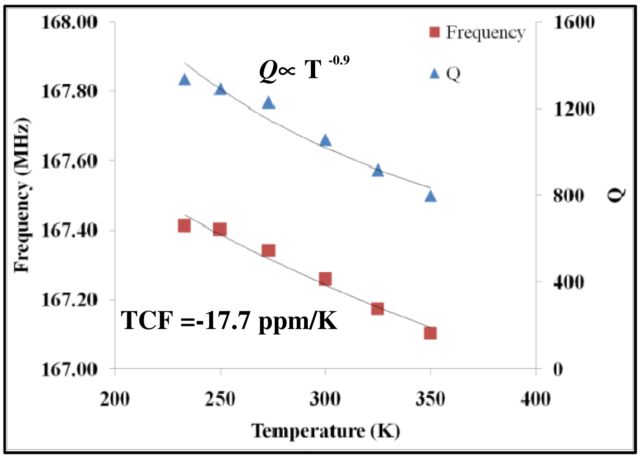


*Figure 7: Temperature measurements in the range of -40ºC to +80ºC indicate that TCF of n-doped GaN is -17.7 ppm/K, while Q is proportional to $T^{-0.9}$, indicating Akhieser regime operation.*

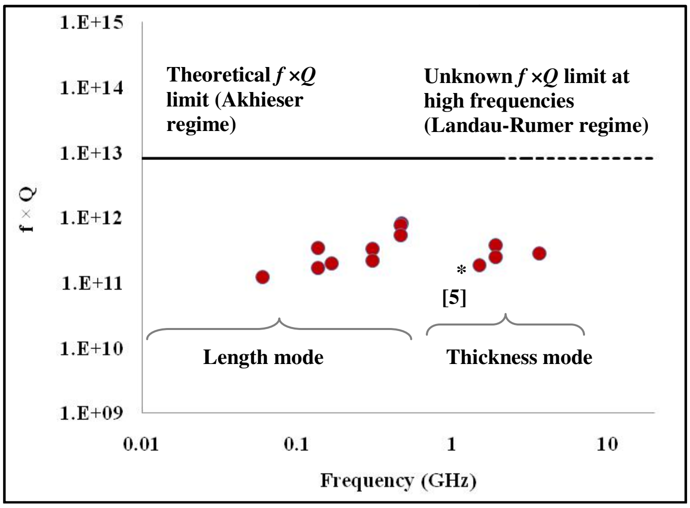


*Figure 8: Measured f×Q product of measured devices from current work and [5] compared with the theoretical limit for GaN [10].*

## Equivalent Model

The motional parameters of the resonators were extracted by fitting the measured results to the modified Butterworth-van Dyke (mBVD) model of a two-port resonator (Fig.9). Fig.10 shows the matched transmission magnitude and phase of Device A. Table 3 details the extracted parameters of this device at 78 K and 3 µTorr, indicating a motional impedance of 430 Ω.

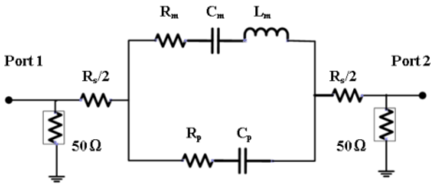
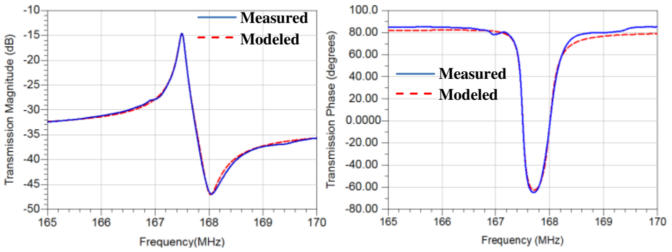


*Figure 9: Two-port mBVD model of the resonators.*



*(a)* *(b)*

*Figure 10: Measured and modeled (a) magnitude and (b) phase of $S_{21}$ for Device A.*

*Table 3: Extracted motional parameters for Device A.*

| $R_m$ (Ω) | $L_m$ (µH) | $C_m$ (fF) | $R_p$ (Ω) | $C_p$ (fF) | $R_s$ (Ω) | Unloaded *Q* |
|---|---|---|---|---|---|---|
| 430 | 767 | 1.771 | 648 | 195.37 | 10 | 1886 |

## CONCLUSION

This work lays the foundation for a systematic investigation into the design aspects of mechanical resonators and filters fabricated from epitaxially grown single crystal GaN. Important material parameters such as the acoustic velocity and effective piezoelectric coupling coefficient have been extracted and agree well with theoretical predictions and previously reported values. Quality factors of the resonators are found to be among the highest measured in GaN so far. Yet, the measured *f×Q* product is more than an order of magnitude below the theoretical limit in the Akhieser regime of phonon-phonon dissipation, indicating that there is much room for improving the performance of such devices. Successful implementation of these devices can make it possible to realize GaN-based microsystems that include high-performance micro-mechanical resonators and filters monolithically integrated with HEMT circuitry.

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