AN 8.7 GHZ GAN MICROMECHNAICAL RESONATOR WITH AN INTEGRATED ALGAN/GAN HEMT

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ABSTRACT

A thickness-mode GaN resonator is presented in this work, showing fourth-order thickness-mode resonance at 8.7 GHz with an extracted quality factor (Q) of 330, exhibiting the highest resonance frequency measured to date on GaN micromechanical resonators with a high *frequency* × Q value of 2.87×10^{12}. With the goal of implementing an all-GaN multi-GHz oscillator, the resonator is monolithically integrated with an AlGaN/GaN high electron mobility transistor (HEMT). The results reported in this paper mark critical steps in development of high-frequency, high-power GaN microsystems.

INTRODUCTION

Gallium nitride (GaN), with a wide band gap of 3.4 eV, and excellent electronic properties, is a prime candidate for high-temperature, high-power, and high-frequency applications. GaN material systems can also benefit from a two-dimensional electron gas (2DEG) induced at AlGaN/GaN hetero-interface. High electron mobility transistors (HEMTs) with 2DEG conducting channel are widely used in power amplifiers in base stations. GaN also shows strong piezoelectric properties and chemical stability, making it a perfect electro-mechanical material. GaN material system allows for incorporation of diverse functionalities on the same substrate. GaN micromechanical resonators and filters, AlGaN/GaN HEMTs, optoelectronic components, and high-Q passives can all be integrated on the same substrate to build GaN-based integrated circuits such as timing references or harsh environments sensors.

Our group has previously reported on bulk-mode GaN micromechanical resonators with frequencies ranging from 10s of MHz to 3 GHz [1, 2]. Higher frequency resonators are sought for use as local oscillators (LOs) in high-power mm-wave GaN transceivers. Higher frequency resonances have been achieved using resonant body HEMTs [3-5], which offer intrinsic filtering and signal amplification. However, the acoustic gain of reported resonant body HEMTs proved to be too small for implementing an LO without the need of external amplifiers. In this work, we demonstrate a piezoelectrically transduced GaN resonator at 8.7 GHz connected to an on-chip AlGaN/GaN HEMT. The resonator is $40 \times 60\ \mu m^2$ (Fig. 1) and exhibits the highest resonance frequency measured for GaN resonators to date. It shows good linearity with third-order input intercept point (IIP_3) of 29.2 dBm. The response of the resonator cascaded with the HEMT is tuned by ~7 dB. Further optimization of the resonator and HEMT allows for realization of multi-GHz all-integrated GaN LOs.

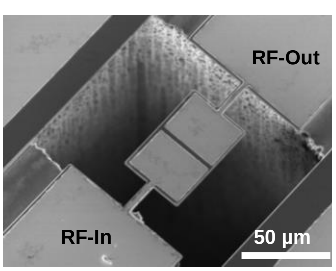


Figure 1. SEM image of a fabricated 40 µm × 60 µm GaN BAW resonator, with tethers of 20 µm in length and 5 µm in width.

GAN MICROMECHANICAL OSCILLATORS

The main goal of this work is to design a GaN MEMS-based oscillator. Two approaches are taken to realize a GaN oscillator in GaN/AlGaN MMIC (Fig. 2): (1) Resonant body HEMTs, shown in [3-5], which are readily scalable to higher frequencies, but suffer from low acoustic gain insufficient for self-oscillation, and (2) cascade of a resonator and a HEMT (focus of this work). Capacitive feed-through, which becomes a critical issue at higher frequencies, can be removed from the resonator response using a dummy, unreleased resonator in a differential amplifier configuration [6], hence allowing to scale the resonant frequencies deep into the GHz regime where GaN ICs usually operate at.

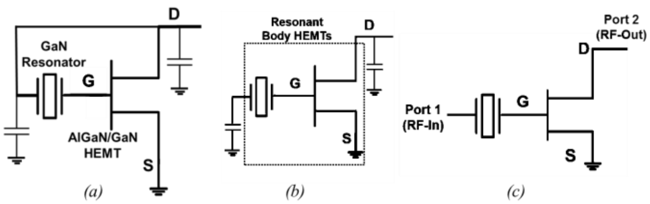


Figure 2. (a) A simple pierce oscillator configuration. (b) A resonator and a transistor can be combined forming a single resonant body HEMT. (c) A cascade of a resonator and a HEMT that is implemented in this work, as the main building block of an oscillator.

DISCUSSION

The GaN resonator of this work consists of a 1.8-µm-thick GaN layer epitaxially grown on a Si substrate by metal-organic chemical vapor deposition (MOCVD) technique. The fabrication process of the resonator and HEMT is reported in [7]. The measured response of the resonator in the frequency range of 1-10 GHz is shown in Fig. 3, along with the corresponding mode shape for each harmonic of the thickness-mode resonance. The fundamental thickness-mode resonance at 2.22 GHz shows an acoustic velocity of ~7920 m/s.

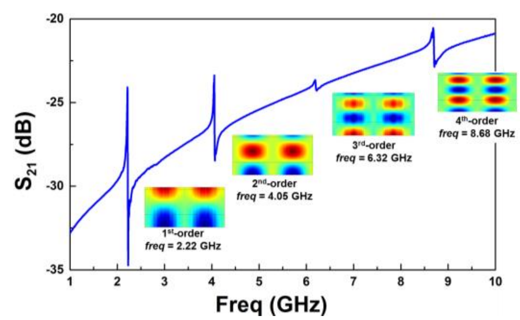


Figure 3. Wide-band frequency response of the 40 µm × 60 µm GaN resonator. The effect of capacitive feed-through is not de-embedded from the response. The mode shape for each thickness-mode resonance is also shown.

The fourth-order thickness-mode harmonic of the resonator shown in Fig. 1, exhibits a Q of 330 at 8.7 GHz, resulting in a high *frequency* × Q (or $f \times Q$) value of 2.87×10^{12} (Fig. 4). Operation at the fourth-order thickness-mode resonance as compared to lower harmonics, primarily benefits from reduction of three loss mechanisms, (1) visco-elastic damping, (2) thermo-elastic damping

(TED), and most importantly (3) phonon-phonon scattering, as the intrinsic material loss is limited by the Landau–Rumer regime at such high frequencies [8], hence larger $f \times Q$ values are expected. With the current tether design, the anchor loss is not the dominant *Q* limiting factor. Whereas, metal loading from both the top and bottom electrode is a source of *Q* degradation, which can be alleviated by using 2DEG as the conductive top/bottom electrode.

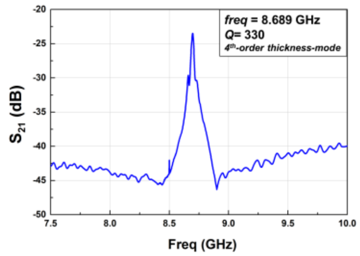
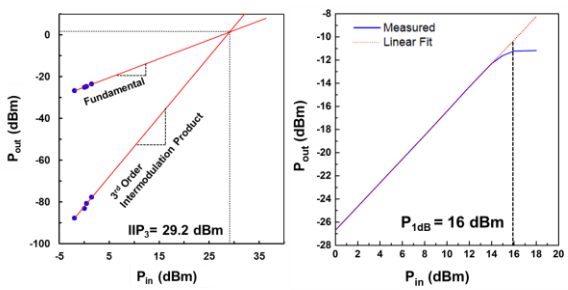


Figure 4. De-embedded frequency response of the 40 µm × 60 µm GaN resonator with a resonant frequency of 8.7 GHz, and an extracted Q of 330 at room temperature and ambient pressure. Capacitive feed-through is de-embedded from the resonator response using an unreleased but otherwise identical resonator.

Owing to its wide band gap and large breakdown electric field, GaN can handle high-power RF signals. GaN HEMTs can deliver 10 times as much output power as their GaAs counterparts. Similarly, GaN MEMS resonators show high power handling capability. The power handling of the resonator is characterized in Fig. 5. The fundamental mode and the third-order intermodulation product are extrapolated, showing an IIP_3 of 29.2 dBm. Furthermore the device shows 1-dB compression at input power level of ~16 dBm, most likely limited by the anchor design.



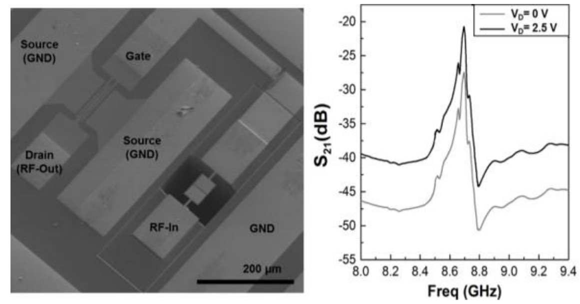
(a) *(b)*

Figure 5. (a) Two-tone power measurement of the fourth-order thickness mode resonance at 8.7 GHz. The extracted IIP_3 value is 29.2 dBm. (b) 1-dB gain compression occurs at input power level of 16 dBm at 8.7 GHz.

An integrated HEMT is used to amplify the response of the GaN resonator. Using this configuration, the signal is amplified by more than 7 dB when the HEMT is switched ON as shown in Fig. 5(b). The $f \times Q$ value reported in this work is compared to previous work, including GaN-on-Si resonators [2], resonant HEMTs [3, 5] (Fig. 7).

CONCLUSION

High-*Q* and high power handling capability of multi-GHz GaN resonators presented in this work suggest that GaN is a strong candidate for low phase-noise, multi-GHz power oscillators. Future work includes co-integration of high-*Q* capacitors and matching networks for implementing an on-chip oscillator using similar GaN-based micromechanical resonators.



(a) *(b)*

Figure 6. (a) An SEM image and (b) the frequency response of a cascade of a resonator and a HEMT. The output of the resonator is fed to the gate of the HEMT, and the output signal is picked up from the drain. The gate DC bias is kept at 0 V. The drain voltage is varied to tune the transistor gain. The insertion loss is improved by ~7 dB when the drain voltage is at 2.5 V.

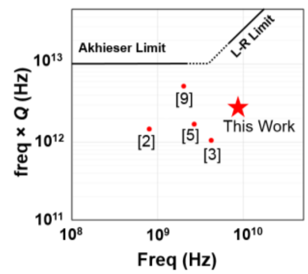


Figure 7. Comparison of f×Q value of GaN-based resonators with the phonon-phonon loss limits.

REFERENCES

[1] V. J. Gokhale, J. Roberts, and M. Rais-Zadeh, "High performance bulk mode gallium nitride resonators and filters," *International Solid-State Sensors, Actuators and Microsystems Conference (Transducers)*, Beijing, 2011, pp. 926-929.

[2] A. Ansari, V. J. Gokhale, V. A. Thakar, J. Roberts, and M. Rais-Zadeh, "Gallium nitride-on-silicon micromechanical overtone resonators and filters," *IEEE Electron Device Meeting (IEDM)*, Washington, DC, 2011, pp. 20.3.1- 20.3.4.

[3] A. Ansari and M. Rais-Zadeh, "A thickness-mode AlGaN/GaN resonant body high electron mobility transistor," *IEEE Transactions on Electron Devices*, Feb. 2014.

[4] A. Ansari and M. Rais-Zadeh, "HEMT-Based readout of a thickness-mode AlGaN/GaN resonator," *IEDM 2013*, Washington, DC, pp. 18.3.1- 18.3.4.

[5] L. C. Popa and D. Weinstein, "Switchable piezoelectric transduction in AlGaN/GaN MEMS resonators," *Transducers* 2013, pp. 2461-2464.

[6] K. E. Wojciechowski, "Single-chip precision oscillators based on multi-frequency, high-Q aluminum nitride MEMS resonators," *Transducers* 2009, Denver, CO, pp. 2126 – 2130.

[7] A. Ansari, V. J. Gokhale, J. Roberts, M. Rais-Zadeh, "Monolithic integration of GaN-based micromechanical resonators and HEMTs for timing applications," *IEDM* 2012, San Francisco, CA, pp. 15.5.1-15.5.4.

[8] R. Tabrizian, M. Rais-Zadeh, and F. Ayazi, "Effect of phonon interactions on limiting the f.Q product of micromechanical resonators," *Transducers* 2009, pp. 2131-2134.

[9] L. Popa, D. Weinstein, "L-Band Lamb Mode Resonators in Gallium Nitride MMIC Technology," *IFCS*, May 2014.

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