GALLIUM NITRIDE (GaN) MEMS LAMB WAVE RESONATORS OPERATING AT HIGH TEMPERATURE UP TO 800°C

Wen Sui, Mark Sheplak, and Philip X.-L. Feng**
Electrical & Computer Engineering, University of Florida, Gainesville, FL 32611, USA

2024 IEEE 37th International Conference on Micro Electro Mechanical Systems (MEMS) | 979-8-3503-5792-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/MEMS58180.2024.10439555

ABSTRACT

We report on the first experimental demonstration of gallium nitride microelectromechanical Lamb wave resonators operating at high temperature up to 800°C, while retaining robust electromechanical resonances at ~32MHz and good quality factor of Q=450 at 800°C. The resonance frequency decreases linearly as temperature is being increased, demonstrating an excellent temperature coefficient of resonance frequency of -10 to -20 ppm/°C. The quality factor gradually decreases from ~2000 to ~300 as temperature increases from room temperature to 700°C, then slightly increases to Q=450 as temperature reaches 800°C. Measured resonances exhibit clear repeatability and consistency during heating and cooling processes, without observable hysteresis. This study helps pave the way for advancing gallium nitride electromechanical transducers into high-temperature and hostile environments.

KEYWORDS

Gallium nitride (GaN), microelectromechanical systems (MEMS), resonator, Lamb wave resonator (LWR), high temperature (HT), harsh environment.

INTRODUCTION

Many integrated systems and transducers encounter thermal environments surpassing the capabilities of today's mainstream robust or high-performance physical sensors. Microelectromechanical systems (MEMS) for high-temperature (HT), harsh-environment applications are becoming increasingly important because they are essential for reducing size, weight, and power (SWaP) in strategic sectors such as automotive, aerospace, turbomachinery, oil well/logging equipment, industrial process control, nuclear power and defense communications [1]. Typical automotive and aerospace systems operate from 20°C to 600°C. Higher temperatures up to and above 900°C occur in extreme environments such as gas turbine engines, nuclear power generators, *etc*. Therefore, MEMS must be meticulously designed and operated, accounting for reduced performance and engineering margins to mitigate risks in HT and hostile environments [2].

Engineering devices for temperatures >600°C faces two main challenges, the first being finding suitable materials and the second being making robust interfaces. When it comes to the material choice, HT tolerance, *e.g.*, a high melting point, is important, but it is not the only requirement. Also, the material performance should not degrade with temperature rise. The challenge of interfacing stems from three sources: (1) transfer of power and signal to and from the device in HT environment, (2) choice of proper materials for the interfaces (*e.g.*, contacts, interconnects) with the same criteria as in choosing material for the device, and (3) thermomechanical effects, *e.g.*, mismatch in thermal expansion coefficients of different materials, and the resulting residual stresses can influence the device operation. To achieve robust design along with accurate modeling and simulation, it is important to understand how the key parameters that determine the performance of MEMS devices change with varying temperature, including the device geometry, material density and the Young's modulus.

Gallium nitride (GaN) has emerged as an important and promising material for high-power and high-frequency electronics thanks to its appealing electrical properties [3], including intrinsic direct bandgap (E_g=3.4eV), excellent breakdown field limit (3.3MV/cm), high carrier mobilities (2000cm^2/(V·s)), and built-in piezoelectricity (2.13pm/V). Further, GaN has excellent mechanical properties (E_Y=250 to 400GPa) and chemical inertness, making it attractive for HT and harsh-environment applications [3]. To date, the highest operating temperatures achieved among GaN and aluminum nitride (AlN) MEMS resonators that have been reported are up to 500°C [4] and 700°C [5], respectively. Lamb wave resonators (LWRs) feature a superposition of both longitudinal and shear waves propagating in a plate, with the resonance frequencies defined by in-plane dimensions, which permits batch fabrication of arrays of piezoelectric MEMS resonators with different frequencies on chip with the same film thickness. Figure 1 summarizes the technical rationales and main multiphysical effects to probe on GaN MEMS LWRs for HT applications.

In this work, we demonstrate GaN LWRs operating at HT up to 800°C (the highest for such MEMS to date) in mTorr vacuum without noticeable degradation. We design and fabricate GaN LWRs in thin film GaN-on-Si. An advanced temperature regulation technique is introduced to realize stable HT testing up to 800°C. The resonance of the GaN LWR has been characterized in a wide temperature range from 25°C to 800°C, including measurements of the excellent temperature coefficient of resonance frequency (TCf) and quality factor (Q) retained at up to 800°C.

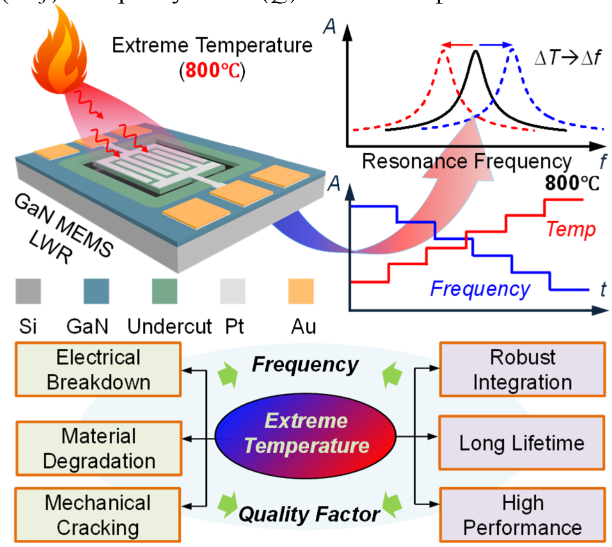

Figure 1: GaN MEMS for HT: technical rationales and main multiphysical effects to probe on this platform.

X-RAY DIFFRACTION (XRD) ANALYSIS

A 2 μm-thick GaN film is epitaxially grown on a Si (111) substrate using organometallic vapor phase epitaxy. Figure 2a shows the XRD analysis results of the GaN thin film. Three GaN peaks confirm the polycrystalline nature with the preferred orientation along the *c*-axis, *i.e.*, 002 peak. The x-ray rocking curves of GaN films grown on Si are measured for (0002) GaN plane, as shown in Fig. 2b, indicating the high crystalline quality.

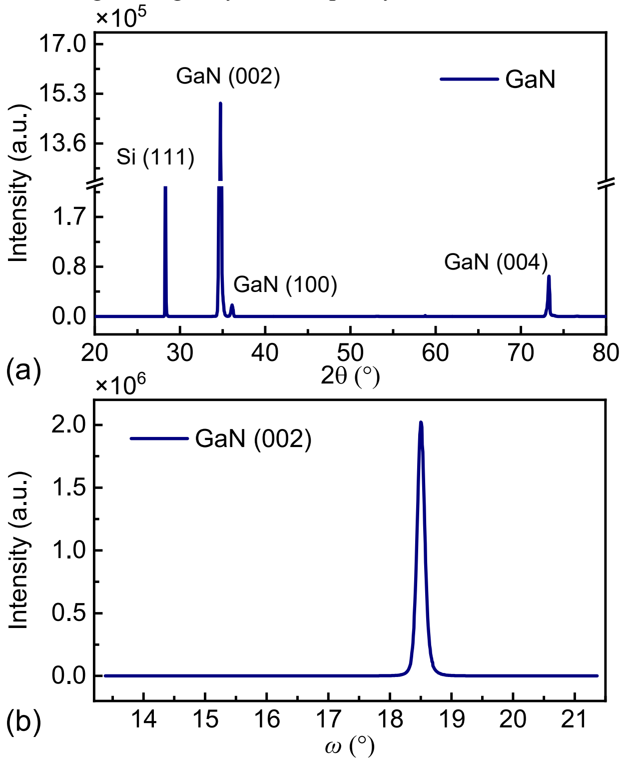

Figure 2: (a) XRD analysis results and (b) rocking curve of GaN (002) peak measured from the 2μm-thick GaN film grown on Si (111) substrate in this work, with a full-width at half-maximum (FWHM) of 0.15°.

DEVICE DESIGN AND FABRICATION

The center frequency of Lamb wave resonator (LWR) can be expressed as [6]

$$f_0 = \frac{v_p}{\lambda}, \quad (1)$$

where λ is the wavelength and v_p represents the acoustic wave velocity. The phase velocity of the lowest order antisymmetric mode (A_0 mode) is related to the thickness of the thin plate [7],

$$v_p = \frac{2\pi h}{\lambda}\sqrt{\frac{E_Y}{12(1-\nu^2)\rho}}\frac{1}{\sqrt{\frac{\pi^2 h^2}{3\lambda^2}+1}}, \quad (2)$$

where h is thickness of the plate, E_Y is Young's modulus, ν is Poisson ratio, and ρ is mass density. The A_0 mode (flexural plate mode) of the LWRs is designed to operate at ~32MHz with λ = 42μm.

The GaN LWRs have been built using a 4-mask fabrication process. First, a chromium (Cr) etch mask is sputtered and patterned for the subsequent dry etching of 2μm GaN thin film in chlorine (Cl_2) based inductively coupled plasma reactive ion etching (ICP-RIE) to define the shape of the suspended GaN resonant body. Following the dry etch, 100nm-thick platinum (Pt) is sputtered and patterned as the interdigital transducers (IDTs) with 10nm titanium (Ti) as the adhesion layer. Then, Au electrode pad is defined by the 3rd photolithography step and a sputtering and liftoff process. After that, the devices are released via a deep reactive ion etch (DRIE) of Si with photoresist as the mask for protecting the metallization layer. Finally, the photoresist is removed gently by O_2 plasma. Figure 3e and 3f show the optical image and SEM image of a GaN LWR with λ=40μm, respectively.

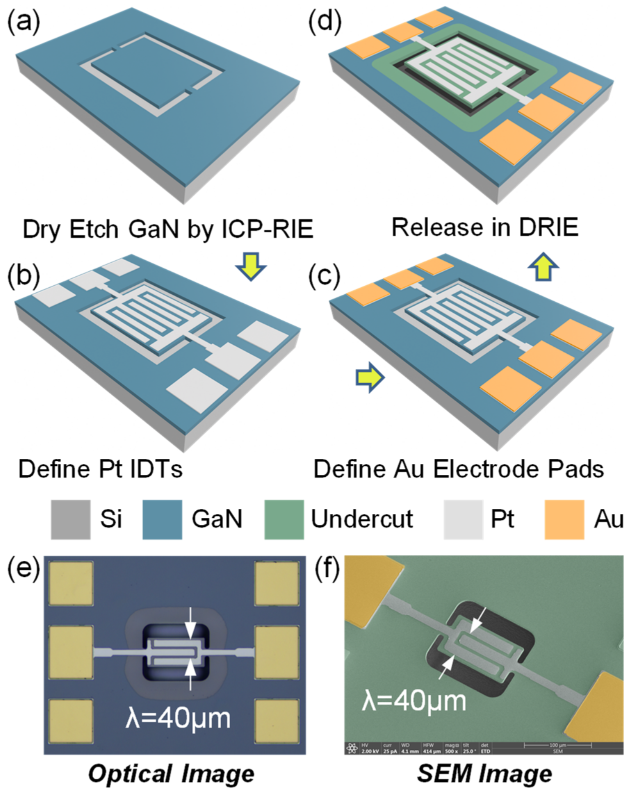

Figure 3: Schematic illustration of fabrication processes for making the GaN LWRs. (a) Dry etch GaN by ICP-RIE. (b) Sputter Pt IDTs and liftoff. (c) Sputter Au electrode pads and liftoff. (d) Release the GaN resonant body by etching Si in DRIE. (e) Optical image and (f) SEM image of a GaN LWR with λ=40μm.

HIGH-TEMPERATURE MEASUREMENT

There are several commonly used methods to heat MEMS devices and perform high-temperature (HT) measurements. The selection of the heating method primarily depends on the specific requirements of the study. The size and geometry of the MEMS device, the temperature range that needs to be covered, and the desired level of temperature control are some of the key factors to consider when choosing the heating method. Here, we use a ceramic heater type customized electrical probing system, as shown in Fig. 4, a miniature probe system with vacuum and temperature control functions. The system is capable of measuring the electrical behavior of MEMS in the range of room temperature to 1000°C. To perform the resonance frequency measurements, the chip is mounted on the ceramic heater and heated to the desired temperature. The temperature is monitored and controlled using the built-in temperature control functions of the system. Once the chip reaches the desired temperature, the resonance frequency of the sample is measured using a network analyzer. To ensure accurate and reliable measurements, the sample is allowed to stabilize at the desired temperature for a sufficient period of time before taking the resonance frequency measurement. Figure 4b shows the temperature regulation in both heating and cooling with the temperature ranging from room temperature to 800°C. At each temperature point, we wait ~10 minutes for the temperature to stabilize and then take the resonance measurement. The inset images depict the device under test at 23°C and 800°C, respectively.

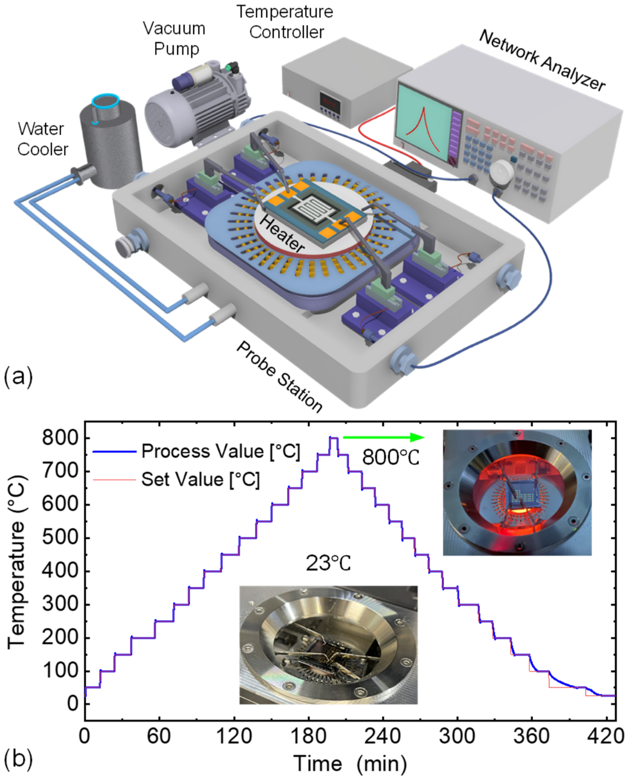

Figure 4: Illustration of the compact HT electrical probe station. (b) Temperature regulation from 23°C to 800°C (heating up to 800°C & cooling back to 23°C).

RESULTS AND DISCUSSIONS

We first measure the resonance of a GaN LWR with λ=42µm in 20mTorr vacuum at room temperature. As shown in Fig. 5a, we observe a resonance frequency at ~32.3MHz. The resonance frequency downshifts as the temperature increases from 23°C up to 800°C. Figure 5b shows the resonance measured at 800°C. We observe a noticeable decrease in the baseline of the resonance curve as the temperature increases. This intriguing phenomenon may be attributed to variations in the electrical conductivity of the probe due to fluctuating thermal conditions. To acquire a clearer comprehension of the temperature-dependent resonance, we subtract the electrical background of the resonance curves obtained at each temperature, during both heating and cooling processes, as depicted in Fig. 5c and 5d. The resonance curves, after background subtraction, unveil a clearly discernible attenuation in the amplitude of resonance with increasing temperature. This observation points to the presence of energy losses at elevated temperatures. Importantly, this experiment reveals a remarkable repeatability and consistency in the MEMS resonances measured during both heating and cooling processes, without measurable hysteresis. This compelling evidence clearly validates the robust operations of the GaN LWR resonators at very high temperature up to 800°C, in ~20mTorr vacuum, without noticeable degradation.

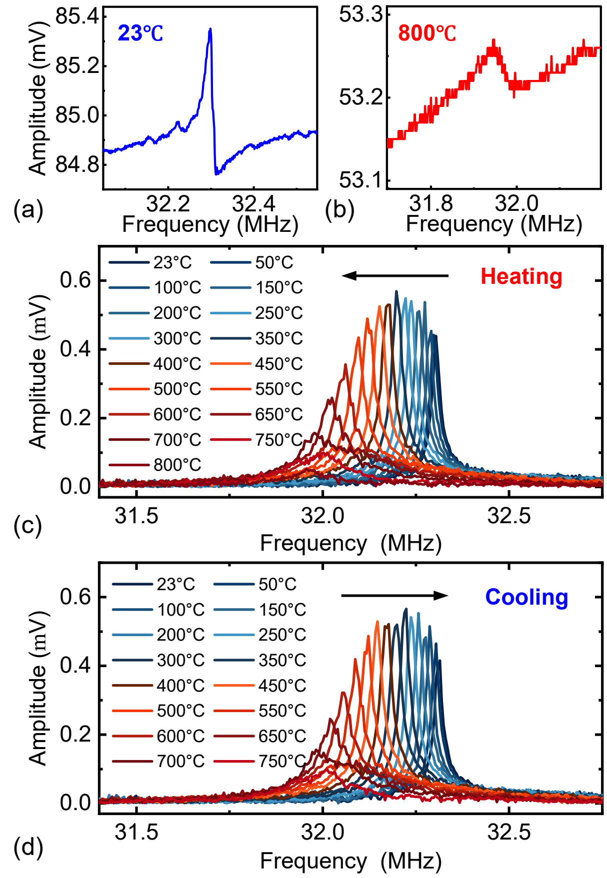

Figure 5: Resonance of a GaN LWR (λ=40µm) measured at (a) 23°C and (b) 800°C. Temperature-dependent resonance of a GaN LWR with λ=40µm, measured in (c) heating and (d) cooling cycles, respectively.

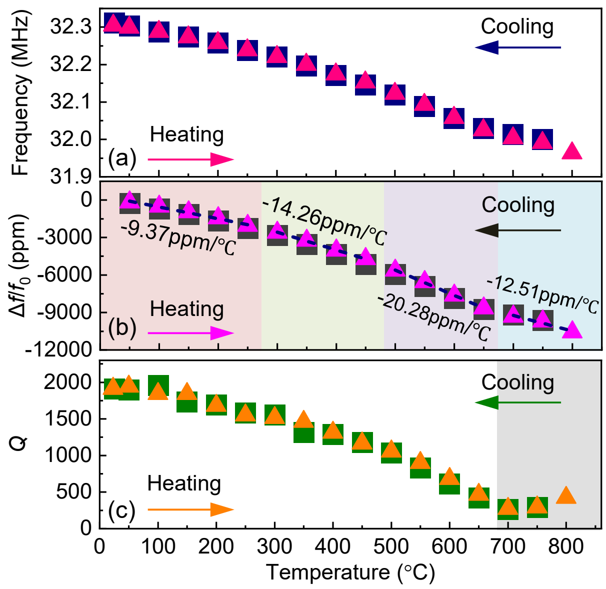

Figure 6: (a) Measured f versus T plot. (b) Measured fractional frequency shift ($\Delta f/f_0$) with varying temperature, where f_0 is the frequency measured at 23°C. (c) Measured Q as a function of temperature.

We observe an almost linear decrease in resonance frequency over a wide temperature range, spanning from 23°C to 800°C (Fig. 6a). Figure 6b presents the TC*f* values obtained by piecewise linear fitting of the fractional frequency shift ($\Delta f/f_0$) data with varying temperature. The very small, excellent TC*f* is within -10 to -20 ppm/°C in the broad temperature range from 23°C to 800°C. As shown in Fig. 6c, *Q* gradually decreases from ~2000 to ~300 as *T* increases from room temperature to 700°C, then slightly increases to *Q*=450 as *T* goes to 800°C.

TC*f* of GaN LWRs has been rarely reported. To date, most of the studies are on GaN surface acoustic wave (SAW) resonators and GaN MEMS operating in flexural modes. TC*f*s have been reported in the range of -30ppm/°C to -80ppm/°C. Figure 7 compares results here with earlier HT GaN SAW devices. Here, our GaN LWRs establish new records in HT (800°C) operations with low TC*f*s (-10 to -20ppm/°C). The variation in TC*f*s reported in different studies underscores the complexity of TC*f*, which is influenced by factors including material properties, device structure, measurement apparatus, temperature regulation techniques, and environmental conditions, *etc*.

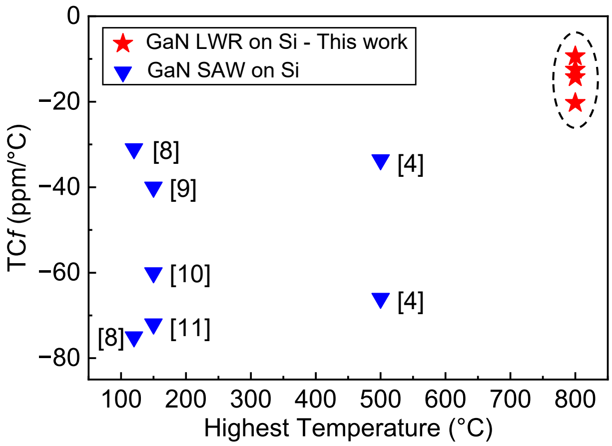

Figure 7: Comparison & benchmarking of GaN LWRs in this work with other high-T GaN MEMS in prior works.

CONCLUSIONS

In conclusion, we have demonstrated the first GaN MEMS LWRs operating at high temperatures up to 800°C in moderate vacuum (~20mTorr). The GaN MEMS LWR exhibit robust resonances at approximately 32MHz and maintain a commendable *Q* of 450 even at 800°C. The measured resonances consistently and robustly maintain their stability throughout both heating and cooling processes without noticeable hysteresis, providing direct validation that GaN LWRs are capable of operating at very high temperatures, with robustness at 800°C and likely even higher. This study not only initiates a new record for GaN MEMS technology, but also opens the doors to the advancement of GaN MEMS transducers, facilitating their deployment in emerging and increasingly demanding high-temperature and hostile environments.

ACKNOWLEDGEMENTS

We thank the financial support from the National Science Foundation (NSF) through the ECCS EAGER Program (Grant ECCS-2221881), and the Air Force Office of Scientific Research (AFOSR) through the Basic Research Program (Grant FA9550-23-1-0304).

REFERENCES

[1] W. Sui, H. Wang, J. Lee, A. Qamar, M. Rais-Zadeh, and P. X.-L. Feng, "AlScN-on-SiC thin film micromachined resonant transducers operating in high-temperature environment up to 600°C," *Adv. Funct. Mater.*, vol. 32, art. no. 2202204, 2022.

[2] W. Sui, T. Kaisar, H. Wang, Y. Wu, J. Lee, H. Xie, and P. X.-L. Feng, "Micromachined thin film ceramic PZT multimode resonant temperature sensor," *IEEE Sensors J.*, 2023, DOI: 10.1109/JSEN.2023.3294125.

[3] M. Rais-Zadeh, V. J. Gokhale, A. Ansari, M. Faucher, D. Théron, Y. Cordier, and L. Buchaillot, "Gallium nitride as an electromechanical material," *J. Microelectromech. Syst.*, vol. 23, pp.1252-1271, 2014.

[4] A. Qamar, S. R. Eisner, D. G. Senesky, and M. Rais-Zadeh, "Ultra-high-Q gallium nitride SAW resonators for applications with extreme temperature swings," *J. Microelectromech. Syst.*, vol. 29, pp. 900-905, 2020.

[5] C. M. Lin, T. T. Yen, V. V. Felmetsger, and A. P. Pisano, "Thermally compensated aluminum nitride Lamb wave resonators for high temperature applications," *Appl. Phys. Lett.*, vol. 97, art. no. 083501, 2010.

[6] M. Liu, J. Li, J. Ma, and C. Wang, "Design and fabrication of a MEMS Lamb wave device based on ZnO thin film," *J. Semicond.*, vol. 32, art. no. 044006, 2011.

[7] M. R. Redwood, *Mechanical Waveguides*. Oxford: Pergamon Press, 1960.

[8] A. Müller, G. Konstantinidis, A. Stefanescu, I. Giangu, A. Stavrinidis, M. Pasteanu, G. Stavrinidis, and A. Dinescu, "Pressure and temperature determination with micromachined GaN/Si SAW based resonators operating in the GHz frequency range," in *Proc. of IEEE Int. Conf. Solid-State Sens. Actuators & Microsyst. (Transducers)*, Kaohsiung, Taiwan, June 18-22, 2017, pp. 1073-1076.

[9] A. C. Bunea, D. Neculoiu, and A. Dinescu, "GaN/Si monolithic SAW lumped element resonator for C-and X-band applications," in *Proc. of IEEE Asia Pacific Microwave Conf. (APMC),* Kuala Lumpur, Malaysia, November 13-16, 2017, pp. 1010-1013.

[10] A. Müller, G. Konstantinidis, V. Buiculescu, A. Dinescu, A. Stavrinidis, A. Stefanescu, G. Stavrinidis, I. Giangu, A. Cismaru, and A. Modoveanu, "GaN/Si based single SAW resonator temperature sensor operatingin the GHz frequency range," *Sens. Actuators A: Phys.*, vol. 209, pp. 115-123, 2014.

[11] A. Müller, G. Konstantinidis, I. Giangu, V. Buiculescu, A. Dinescu, A. Stefanescu, A. Stavrinidis, G. Stavrinidis, and A. Ziaei, "GaN-based SAW structures resonating within the 5.4–8.5 GHz frequency range for high sensitivity temperature sensors," in *Proc. of IEEE MTT-S Int. Microwave Symp.*, Tampa, FL, USA, June 1-6, 2014, pp. 1-4.

CONTACT

*Wen Sui: wen.sui@ufl.edu
*Philip Feng: philip.feng@ufl.edu