Abstract—This article presents a comprehensive study of the performance of Sezawa surface acoustic wave (SAW) devices in SweGaN QuanFINE ultrathin GaN/SiC platform, reaching frequencies above 14 GHz for the first time. Sezawa mode frequency scaling is achieved due to the elimination of the thick buffer layer typically present in epitaxial GaN technology. Finite element analysis (FEA) is first performed to find the range of frequencies over which the Sezawa mode is supported in the grown structure. Transmission lines and resonance cavities driven with interdigital transducers (IDTs) are designed, fabricated, and characterized. Modified Mason circuit models are developed for each class of devices to extract critical performance metrics. We observe a strong correlation between measured and simulated dispersion of the phase velocity ($v_p$) and piezoelectric coupling coefficient ($k^2$). Maximum $k^2$ of 0.61% and frequency-quality factor product ($f \cdot Q_m$) of $6 \times 10^{12}$ s$^{-1}$ are achieved for Sezawa resonators at 11 GHz, with a minimum propagation loss of 0.26 dB/λ for the two-port devices. Sezawa modes are observed at frequencies spanning up to 14.3 GHz, achieving a record high in GaN microelectromechanical systems (MEMS) to the best of the authors’ knowledge.

Index Terms—5G/6G, delay lines, GaN on SiC, Internet of Things (IoT), Mason model, resonators, radio frequency (RF) microelectromechanical systems (MEMS), surface acoustic wave (SAW), SAW interdigital transducers (IDTs).

I. INTRODUCTION

SURFACE acoustic wave (SAW) devices are essential components for filters, oscillators, and radio frequency (RF) signal processing blocks in wireless communication due to their advantages of lithographically defined resonance frequency, simple fabrication process despite the use of materials that have historically been difficult to etch, low manufacturing cost, and low sensitivity to acceleration [1], [2], [3]. They are also widely used in sensor applications due to SAW sensitivity to various environmental factors including temperature, pressure, viscosity, humidity, etc. at the surface of the device [3], [4], [5], [6]. However, a technology gap in growth and material quality has thus far limited the scaling of SAW frequencies with low losses required for super high frequency (SHF) microelectromechanical systems (MEMS) components for 5G/6G and the Internet of Things (IoT). Frequency scaling is also beneficial for SAW sensors as their sensitivity increases with the resonance frequency [7], [8], [9].

Sezawa acoustic waves in a technology platform such as GaN on SiC provide a much-needed solution due to high phase velocity to scale to higher frequencies for given lithographic feature sizes, with the added benefits of high piezoelectric coupling and low viscoelastic losses [10], [11]. This mode exhibits improved confinement within the piezoelectric layer relative to the Rayleigh mode due to a mismatch in the acoustic impedance between the GaN epilayer and the SiC substrate, which reduces leakage through the substrate [3], [12], [13]. In contrast with suspended acoustic structures, Sezawa mode devices are solidly mounted to the bulk substrate, in this case, SiC, which provides excellent thermal conductivity improving power handling and frequency stability [14]. The ability
Highlights

- Experimental demonstration and performance analysis of SAW devices in a buffer-free and ultrathin GaN/SiC platform for the first time, reaching a record high resonance frequency up to 14.3 GHz.
- Maximum electromechanical coupling ($k^2$) of 0.61% and frequency-quality factor product ($f.Q_m$) of $6 \times 10^{12}$ s$^{-1}$ for Sezawa mode resonators at 11 GHz, with a minimum acoustic propagation loss ($\alpha$) of 0.26 dB/\text{\AA} for the two-port devices.
- A promising GaN MMIC technology with a high 2DEG density in AlGaN/GaN heterostructure for low-cost and high-performance reconfigurable MEMS components for programmable ad-hoc radios and SAW sensors for harsh environments.

II. QuanFINE$^1$ GaN-on-SiC Platform

Sezawa mode devices are designed in SweGaN’s QuanFINE$^1$ platform which consists of a heterostructure of AlGaN/GaN with a low defect density unintentionally doped (UID) thin GaN channel layer [see Fig. 1(a)] [25]. An ultrathin AlN nucleation layer (NL) is first grown on semi-insulating 4H-SiC to initiate the high-quality growth of the structure in a metal-organic chemical vapor deposition (MOCVD) reactor [27], [28], [29]. The QuanFINE$^1$ process does not require a thick, doped buffer layer typical in conventional GaN MMICs. A high-quality in situ SiN passivation layer is introduced on the AlGaN barrier layer to protect the sensitive surface from external damage. High-resolution transmission electron micrographs (TEMs) of the GaN/AlN and AlN/SiC interfaces [see Fig. 1(b)] demonstrate grain-free boundaries with low void and dislocation density that are essential for high-performance MEMS and MMIC devices [27]. The AlN NL significantly improves heat dissipation from the GaN channel to the high-thermal-conductivity SiC substrate due to its outstanding crystalline quality and ultralow thermal boundary resistance (TBR), making the structure ideal for high-power operation [25]. X-ray diffraction rocking curves (XRCs) exhibit full width at half maximum (FWHM) of 86 arcsec and 272 arcsec for the GaN (002) and GaN (102) reflections [see Fig. 1(c)]. These measurements correspond to a reduction in defect density of two orders of magnitude when compared with typical
GaN epilayers of similar thickness [27], [30], enabling low viscoelastic losses for GaN electromechanical devices [20].

III. Finite Element Analysis Simulation

The presence of SHF Sezawa modes in the QuanFINE™ heterostructure is confirmed through 2-D finite element analysis (FEA) simulation using COMSOL Multiphysics. Eigenmode analysis is performed on a unit cell spanning one acoustic wavelength (λ) and interdigital transducer (IDT) width (W_{IDT}) and gap each spanning one-quarter wavelength (λ/4). The 2-DEG formed in the heterostructure can be used to block electromechanical actuation by shielding the electric fields from penetrating inside the piezoelectric layers [31]. For this fundamental study of mode propagation, the 2-DEG along with the AlGaN barrier and SiN passivation layers in the QuanFINE™ structure are therefore removed during the fabrication process and are not included in the unit cell simulation. A pair of Ni IDT fingers with a thickness of 80 nm is included to capture the effects of mass loading and interface on the resonance mode [32], [33]. Boundary conditions (BCs) are defined as free on the top of the unit cell geometry, and periodic on both sides of the unit cell. A perfectly matched layer (PML) is introduced at the bottom of the unit cell with fixed BC to simulate radiative losses into the thick SiC substrate. A contour plot of total displacement shows the Sezawa mode in the structure at resonance [see Fig. 2(a)]. Simulated one-port admittance response (Y_{11}) between signal and ground terminals for a wavelength of 400 nm exhibits resonance (f_s) and anti-resonance (f_p) frequencies at 14.23 and 14.26 GHz, respectively [see Fig. 2(b)].

IV. Fabrication and Characterization

SAW devices are fabricated on a QuanFINE™ substrate using a two-mask process. We begin with a shallow blanket etch of in situ SiN and AlGaN layers using CHF_3/O_2 and BCl_3/Cl_2 plasma inside an inductively coupled plasma–reactive ion etcher (ICP-RIE) [see Fig. 3(a)]. A 10–20 nm etch of the GaN channel is performed to ensure the complete removal of the 2-DEG heterojunction. E-beam lithography is used to pattern the IDTs followed by evaporation of Ti(5 nm)/Ni(75 nm) [see Fig. 3(b)]. Finally, Ti(5 nm)/Au(245 nm) is evaporated and patterned with lift-off using photolithography for the low-resistance pads and routings [see Fig. 3(c)]. Atomic force microscopy (AFM) measurements of the root mean square (rms) roughness of the surface before and after shallow etch [see Fig. 3(d) and (e)] confirm good surface morphology, a necessary property for low propagation loss of the Sezawa mode devices.

Four different types of designs for Sezawa mode devices are studied in this work, including: 1) one-port IDT; 2) one-port resonators confined by shorted metal with one IDT set centered in the cavity; 3) two-port delay lines consisting of two IDT ports separated by an acoustic transmission region; and 4) two-port resonators with metal reflectors forming a resonance cavity and two IDT sets for drive and sense embedded within the cavity. Schematic illustrations alongside optical micrographs of these four are provided in Fig. 4(a)–(d). Fig. 4(e) shows a scanning electron micrograph (SEM) of the corner of a one-port resonator, with Ti/Ni transducers, reflectors, bus, and Ti/Au pad.

The devices are measured at room temperature in an RF probe system (Cascade PMC 200) under a vacuum. RF input signal of ~15 dBm is applied using ground-signal-ground (GSG) probes (|Z|, 150 μm pitch) with 50 Ω termination and scattering parameters (S-parameters) are obtained by a parametric network analyzer (Agilent N5225A). Short-open-load-through (SOLT) calibration is performed prior to measurement. The devices under test are then de-embedded from the measured frequency response using open and short structures fabricated on-chip to eliminate electrical parasitics from probe pads and routing to the devices.

V. Results and Discussion

A. Equivalent Circuit Models

The cross-field Mason model [34], [35] is modified by adding lumped elements to extract key electromechanical parameters from the measured data for different Sezawa mode devices shown in Fig. 4(a)–(d). The cross-field model was chosen due to its more accurate representation of the SAW
devices for a wide variety of material platforms as suggested by the literature and the confinement of Sezawa mode inside ultrathin piezoelectric layers on the high resistive substrate in our case [34], [36], [37], [38], [39]. Extracting parameters using the same circuit models in this work provides a common platform to analyze and compare the performances of different SAW designs. Schematic illustrations of the equivalent circuit models for the four different SAW designs are shown in Fig. 5(a)–(d). For all designs under consideration, a unit cell containing a single IDT finger normalized to the aperture [see Fig. 5(e)] is modeled by transmission lines with normalized acoustic impedance for free (\(Z_f\)) and metalized (\(Z_m\)) regions of the structure [see Fig. 5(f)]. The phase angles of the transmission lines (\(\phi_f\), \(\phi_m\)) corresponding to the propagation of the acoustic waves are determined from the finger metallization ratio (\(m\)) of the IDT, and the free (\(v_f\)) and metalized (\(v_m\)) acoustic velocities calculated for wavelength (\(\lambda\)) [36]. The transformer ratio (\(\eta\)) corresponds to the efficiency of energy conversion from the electrical to the acoustic domain and vice versa. The capacitance between IDT fingers, including the feedthrough component within the piezoelectric layers, is represented by \(C_o\). Finally, electrical losses associated with the piezoelectric transducer are captured in the lumped \(R_o\) [40]. To construct the complete model, acoustic ports are cascaded in series, with parallel connection of electrical ports to construct the full N-finger IDT RF port from each IDT pair modeled. The polarity of the transformer swaps for the alternating fingers to model the signal and ground terminals.

As the IDT fingers are electrically shorted at the ends for the reflectors of the resonators, transmission lines representing the acoustic domain without any lumped element are used to denote a unit cell for each finger [see Fig. 5(g)]. A lossy transmission line of impedance \(Z_f\) and phase angle \(\phi_p\) is also included in the Mason model for two-port delay lines and resonators to model the acoustic propagation region in the middle [see Fig. 5(h)]. Additionally, a shunt \(C_f-R_f\) branch is used to model electromagnetic feedthrough signal directly between the two ports associated with shorter delay paths [41]. Finally, free propagation away from the structure and its ends are represented by \(Z_f\) termination, and electrical resistance and inductance inherent to the pads and transducer fingers are modeled by a series \(R_f-L_f\) branch.

### B. Frequency Responses

Measured frequency spectra for Sezawa mode IDTs, delay lines, and resonators are shown in Fig. 6(a)–(d). Based on the FEA simulation results, we designed five different Sezawa mode devices for each design category (see Fig. 4) with an IDT width/gap between 100–375 nm to investigate a wide operating frequency ranging from 5–14 GHz. The aperture (\(L\)) and length of the acoustic transmission path (\(D\)) of the devices are selected as an integer multiple of the wavelength (\(n\lambda\)). The IDTs in the reflectors have the same width, gap, and aperture as that of the ports. Measured data from different designs exhibit minimum and maximum resonance frequencies of 5.4 and 14.3 GHz for the IDT width/gap of 375 and 100 nm, respectively. So, SAW devices in the QuanFINE\textsuperscript{1} platform exceed resonance frequencies of the state-of-the-art GaN resonators using Rayleigh (8.5 GHz) [24], Sezawa (9.1 GHz) [24], and thickness (8.7 GHz) [42] modes having a comparable IDT resolution. Modified Mason circuit models developed in Fig. 5 for different designs are implemented in Keysight Advanced Design System (ADS) software, and measured data are fit to extract key performance matrices, e.g., electromechanical coupling coefficient (\(k^2\)), propagation loss (\(a\)), etc. Extraction of circuit parameters (see Fig. 5) for modified Mason model using ADS software requires the systematic fitting of measured reflection (\(S_{11}, S_{22}\)) and transmission (\(S_{12}, S_{21}\)) spectra incorporating analytical equations and initial values obtained from material properties and geometry of the devices as discussed in [36]. Only the fundamental Sezawa mode in the frequency response is fit by the modified Mason model to avoid computation complexities due to a large number of parameters that would arise to incorporate the spurious mode in the model. The zoomed insets of Fig. 6 show ADS fitting with the measurement of the magnitude and phase responses for the IDTs and resonators, and group delay [43] for the delay lines validating our circuit models (see Fig. 5) for the 150 nm IDT devices. Parasitic feedthrough for the shorter delay paths and higher-order mode coupled with the fundamental Sezawa mode [12] could explain the mismatch between measured and fit responses, particularly for the two-port devices in the insets of Fig. 6(c) and (d). Further analysis in the design space is required for Sezawa.
devices in the QuanFINE\textsuperscript{1} platform to operate in the single-mode condition, including apodization of the duty cycle of the IDTs, selection of the number of IDT pairs in the ports and reflectors, and adjustment of IDT metal thickness \[12\].

**C. Phase Velocity**

The dependence of phase velocity \(v_p\) on the normalized piezoelectric thickness \(h_p/\lambda\) for the Sezawa mode in the QuanFINE\textsuperscript{1} structure is obtained from simulated and measured resonance frequency \(f_s\) using the following equation \[7\]:

\[
v_p = f_s \lambda.
\] (1)

Fig. 7 confirms the high phase velocity of the Sezawa mode in the GaN/SiC platform. A gradual reduction in phase velocity is observed as the acoustic wavelength reduces, presenting a limiting factor for the frequency scaling of Sezawa mode devices for a given lithographic resolution. Experimental
results obtained from different SAW designs (see Fig. 6) agree well with the 2-D FEA simulation.

D. Electromechanical Coupling Coefficient

Series ($f_s$) and parallel ($f_p$) resonance frequencies (see Fig. 2) obtained from the FEA simulation are used to determine the electromechanical coupling ($k^2$) for the Sezawa mode by the following equation [44]:

$$k^2 = \frac{\pi^2 - 4}{4} \left(1 - \frac{f_s}{f_p}\right). \tag{2}$$

$k^2$ are also calculated from the extracted circuit parameters via fitting the measurements (see Fig. 6) using the modified
Mason models (see Fig. 5) with the following equation [35].

\[ k^2 = \frac{\eta^2}{2f_zC_oZ_f} \left[ \frac{J\{\sin(m \frac{\pi}{2})\}}{J\left(2^{-\frac{1}{2}}\right)} \right]^2. \]  

(3)

Here, \( J \) is the Jacobian elliptic integral [45], \( k^2 \) extracted by fitting with the modified Mason models (see Fig. 5) follows the trend with the simulation results for all devices, validating the use of these circuit models. Fig. 8 exhibits a maximum \( k^2 \) value of 0.61% at 11 GHz for a two-port resonator. Considering a unit cell for the IDT fingers normalized to the device aperture [see Fig. 5(e)] and lumped resistance (\( R_s \)) for the distributed losses associated with the IDTs [see Fig. 5(a)–(d)] can explain the deviation in the measurements as compared to the 2-D FEA simulations. In all cases, \( k^2 \) arrives at a maximum value around \( h_p/\lambda \sim 0.5 \), but decreases gradually with lower or higher values of \( h_p/\lambda \). This trend is expected based on the confinement of the Sezawa mode inside the metal IDTs for shorter wavelengths and excessive penetration of the mode into the non-piezoelectric SiC substrate in the case of longer wavelengths. The selection of GaN thickness is necessarily a critical design consideration to achieve the desired frequency range of high-efficiency Sezawa mode devices.

According to theoretical analysis, a maximum \( k^2 \) of 1.3% and \( \sim 2\% \) can be achieved for in-plane and thickness mode devices, respectively, in the GaN platform [11], [46]. Piezoelectric coupling \( k^2 \) depends on the acoustic mode of vibration, with SAW modes typically demonstrating lower \( k^2 \) compared to the thickness mode devices [11]. Fig. 9 shows a comparison between the maximum \( k^2 \) obtained from our Sezawa mode devices and the state-of-the-art MEMS resonators available in the literature [12], [13], [44], [42], [47] in GaN MMICs. The resonators in this work show \( 2\times \) higher \( k^2 \) compared to previously reported Sezawa mode resonator in GaN/SiC, and similar \( k^2 \) with the thickness mode device in GaN [42]. The relatively high coupling in our devices provides an insight into the defect-free crystalline quality of the piezoelectric layers and the effective confinement of acoustic energy for Sezawa mode due to acoustic waveguiding in the QuanFINE\textsuperscript{1} material stack.

Although the maximum \( k^2 \) achieved from the SAW devices (0.61% at 11 GHz) may seem low for wideband filter application, it can be further extended by incorporating high \( k^2 \) materials such as GaScN [48] or AlScN [49] in the QuanFINE\textsuperscript{1} structure, or by implementing active transduction mechanisms as in [50]. This work primarily focuses on the feasibility of the platform for MEMS components in the SHF regime and the inclusion of Sc doping in the GaN/AlN stack requires further study. Nonetheless, the devices in this work, with their low propagation loss, can be useful as SAW sensors having high sensitivity due to super-high operating frequencies [7], [8], [9].

**E. Propagation Loss**

Modified Mason circuit models developed in Section V-A (see Fig. 5) are used to extract propagation loss (\( \alpha \)) associated...
with the acoustic transmission path in two-port delay lines and resonators [see Fig. 6(c) and (d)]. Propagation loss is an important performance metric for the two-port devices where acoustic wave attenuates while traveling through a lossy medium between RF ports. Dispersion of the loss with the normalized piezoelectric thickness shown in Fig. 10 reaches a minimum value of 0.26 dB/λ at 11 GHz. For higher $h_p/\lambda$ values, the Sezawa mode is mainly confined at the upper portion of the GaN channel, likely making surface defects a dominant factor for the higher propagation loss. For lower $h_p/\lambda$, the propagating acoustic wave penetrates deeper into the GaN/AlN/SiC interfaces resulting in higher interfacial loss and substrate radiation [51].

**F. Frequency-Quality Factor Product**

A modified Butterworth-Van-Dyke (mBVD) model [47], [52] [see Fig. 11(a)] is used to extract the frequency-quality factor product ($fQ_m$) of our one-port resonators [see Fig. 6(b)] to benchmark their performance with the state-of-the-art MEMS devices in GaN MMICs. A series $R_m-L_m-C_m$ branch is used to represent the acoustic behavior for series resonance, a shunt $C_{s}-R_s$ branch denotes capacitance and electrical losses of the piezoelectric transducer, and an $L_s-R_s$ branch models series electrical losses for the IDTs and pads. Multiple motional branches $(R_m-L_m-C_m)$ are connected in parallel [see Fig. 11(a)] to fit the fundamental Sezawa mode alongside spurious and higher-order modes for those devices exhibiting such nonidealities. A sample mBVD model fit of measured reflection ($S_{11}$) by ADS for both fundamental and spurious modes of a 150 nm IDT device is shown in Fig. 11(b). The unloaded or mechanical quality factor ($Q_m$) and loaded quality factor ($Q_l$) of a particular acoustic mode is obtained using the following equations [47], [53]:

$$Q_m = 2\pi f_s \frac{L_m}{R_m},$$

$$Q_l = 2\pi f_s \frac{L_m}{R_m + R_s},$$

Fig. 11(c) shows the measured dependence of $Q_m$ and $Q_l$ on the resonance frequency extracted using the mBVD model of five one-port resonators [see Fig. 6(b)]. Fig. 11(c) also includes $Q_m$ and $Q_l$ for higher-order spurious modes that exist in the frequency responses of 9 GHz (200 nm IDTs) and 11 GHz (150 nm IDTs) devices [see Fig. 6(b)]. As the width ($W_{IDT}$) and aperture ($L$) of the IDTs in the resonators are scaled according to the wavelength ($\lambda$), the series resistances for all devices are similar ($R_s \sim 10\, \Omega$). However, comparable motional resistance ($R_m \sim 90\, \Omega$) with $R_s$ for the fundamental mode causes $\sim 10\%$ lower $Q_l$ than $Q_m$ for 9 and 11 GHz devices. The rest of the resonators exhibit significantly higher $R_m$ ($\sim 1\, \kappa\Omega$) than $R_s$ due to the dispersion of the Sezawa mode in the QuanFINE platform for the layer thickness provided, which results in a similar $Q_l$ to $Q_m$.

A maximum $Q_m$ of 542 at 11 GHz is achieved from our resonators as shown in Fig. 11(c). Conversion of the minimum propagation losses [20] (0.26 dB/λ) obtained from the two-port devices in Fig. 10 results in $Q_m$ of 104, which is $5 \times$ lower compared to that of the resonators. The lower $Q_m$ of the two-port transmission structures points to scattering at the interface of the IDT and metal-free propagation region. In the resonator, the periodic metallization continues seamlessly into the reflectors, preventing this radiative loss mechanism. This
observation is supported by the FEA simulation available in the literature [54].

The \( f \cdot Q_m \) product for each resonator is calculated by multiplying the resonance frequency \( (f_r) \) of a mode by its extracted \( Q_m \). Fig. 12 compares the \( f \cdot Q_m \) product obtained for the fundamental mode of our resonators against Sezawa mode devices on different substrates [12], [13], [24] as well as other electromechanical modes [24], [42], [47] in GaN MMICs, alongside the fundamental limits obtained from the theoretical calculation for the phonon-phonon scattering in GaN [20]. A maximum \( Q_m \) of 542 results in an \( f \cdot Q_m \) product of \( 6 \times 10^{12} \text{ s}^{-1} \) at 11 GHz, which is 6× higher compared to the resonators previously reported as a record high frequency (9.1 GHz) in the literature for Sezawa GaN [24]. Scattering of acoustic waves due to the phonon-electron interaction in the UID GaN layer and mass loading for the metal IDTs can result in \( f \cdot Q_m \) product lower than the theoretical limits [20]. Although Lamb mode resonators at 1.87 GHz in [47] showed \( f \cdot Q_m \) products close to the fundamental limits, narrow tether design, and non-linearity associated with the thin membrane of the released devices make them challenging to scale to the SHF regime.

It should be noted that the mBVD model in this work is implemented to complement the modified Mason model rather than verify it. The mBVD model provides a more accurate extraction of the quality factor for the one-port resonator, including the presence of spurious modes, due to the reduced number of variables in mBVD [see Fig. 11(a)] relative to the modified Mason model [see Fig. 5(b)]. Since spurious modes are not fit by the modified Mason model in this work due to computational complexity, it would be inappropriate to make a direct comparison between parameters extracted from the Mason model with that of the mBVD model. Meanwhile, the modified Mason model is more appropriate for fitting two-port devices with an accurate representation of the acoustic propagation region between transducers. The modified Mason model thereby provides a common platform for all four types of SAW designs in Fig. 4(a)–(d) to investigate and compare the dispersion of phase velocity and coupling coefficient for the fundamental Sezawa mode. Finite element modeling in COMSOL Multiphysics checks the consistency of the model, benchmarking the extracted parameters as shown in Figs. 7 and 8.

VI. CONCLUSION

The QuanFINE\(^1\) platform is shown in this work to enable frequency scaling beyond the state-of-the-art MEMS devices in GaN MMICs with simple fabrication. Extracted phase velocity and electromechanical coupling from modified Mason model fittings for different SAW designs show the dispersion of the Sezawa mode in the structure and close agreement with FEA simulation. The resonators exhibit low propagation loss and high frequency-quality factor product toward the fundamental limits at record high frequency in GaN MMICs. This technology with AlGaN/GaN heterostructure and high 2-DEG density provides a platform for low-cost and high-performance reconfigurable MEMS components in GaN MMICs for programmable ad hoc radios in the SHF regime [55], [56], and opening doors for high-performance SAW sensors, monolithically integrated with peripheral active circuitry in GaN MMICs for harsh environments [57], [58].

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Fig. 12. \( f \cdot Q_m \) product with frequencies for the fundamental Sezawa mode of the resonator in this work compared with other MEMS devices in GaN MMICs and the theoretical limits of phonon-phonon scattering for GaN.
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