Experimental Characterization of the Thermal Time Constants of GaN HEMTs via Micro-Raman Thermometry

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Abstract—Gallium nitride (GaN) high electron mobility transistors (HEMTs) are a key technology for realizing next generation high power RF amplifiers and high efficiency power converters. However, elevated channel temperatures due to self-heating often severely limit their power handling capability. Although the steady-state thermal behavior of GaN HEMTs has been studied extensively, significantly fewer studies have considered their transient thermal response. In this work, we report a methodology for measuring the transient temperature rise and thermal time constant spectrum of GaN HEMTs via time-resolved micro-Raman thermography with a temporal resolution of 30 ns. We measured a broad spectrum of time constants from ≈130 ns to ≈3.2 ms that contribute to the temperature rise of an un gated GaN-on-SiC HEMT due to aggressive, multidimensional heat spreading in the die and die-attach. Our findings confirm previous theoretical analysis showing that one or two thermal time constants cannot adequately describe the transient temperature rise and that the temperature reaches steady-state at ≈16L^2/π^2α, where L and α are the thickness and thermal diffusivity of the substrate. This work provides a practical methodology for validating transient thermal models of GaN HEMTs and for obtaining experimental values of the thermal resistances and capacitances for compact electro-thermal modeling.

Index Terms—GaN HEMTs, micro-Raman thermometry, time-resolved, self-heating, pulse DC bias.

I. INTRODUCTION

Gallium nitride (GaN)-based high electron mobility transistors (HEMTs) are one of the most promising compound semiconductor technologies for high power radio-frequency (RF) amplifier and high voltage power conversion applications [1]-[2]. However, the very high dissipated power densities present in GaN-based discrete transistors and monolithic microwave integrated circuits (MMICs) often result in elevated channel temperatures, which need to be accurately characterized and managed to ensure proper device performance and reliability. The most popular experimental temperature measurement techniques for this technology include micro-Raman thermometry [3]-[12], thermoreflectance microscopy [5],[13]-[14], and electrical parameter-based thermometry [15]-[17].

While the majority of reports in the literature have focused on characterizing the steady-state temperature rise of GaN HEMTs at constant dissipated power or under DC bias conditions, GaN HEMTs are often subject to pulse DC or RF bias conditions. For instance, GaN-based power amplifiers are often operated in pulse mode, in which the dissipated power is a strong function of time and the peak dissipated power is an order of magnitude higher than the average dissipated power [18]. Thus, there is a great need to more extensively characterize the transient temperature rise in GaN HEMTs under transient power dissipation. Although transient thermal modeling using finite element analysis (FEA) techniques can provide useful channel temperature predictions under pulse DC bias conditions [19]-[21], validating thermal models with temperature measurements as close to the channel as possible is critical.

Over the last fifteen years, micro-Raman spectroscopy has become one of the most popular techniques for measuring the steady-state temperature rise of GaN HEMTs owing to its high spatial resolution of ≈1 µm and the wide availability of commercial micro-Raman systems [3]-[5]. Time-resolved micro-Raman thermometry has also been demonstrated with a temporal resolution of 10 to 15 ns by externally modulating the laser excitation and synchronizing the laser pulses with a pulse DC bias applied to the device [6]-[12]. While measuring the temperature response to a particular pulse DC bias condition is helpful, the greatest value of the technique is the potential to characterize the thermal time constant spectrum from which the temperature response to any transient bias can be predicted. Previous studies have suggested that the temperature rise of GaN on 300 µm thick silicon carbide (SiC) HEMTs increases rapidly over the first ~1 µs and then rises slowly with a time constant of ≈10 µs [6]-[9]. However, these previous studies acknowledge partial funding support from the ONR PECASE program monitored by Dr. Paul Maki.

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have not provided a systematic methodology for measuring the full spectrum of thermal time constants from ~100 ns to the time at which the device temperature reaches its steady-state value. Our recent theoretical analysis of transient heat conduction in GaN HEMTs suggests that the reported time constant of ~10 µs may not be capturing the true long time behavior as 3-D heat conduction theory predicts the longest time constant to be ~200 µs for a GaN HEMT on 300 µm thick SiC substrate [22].

In this work, we describe an experimental methodology for characterizing the transient temperature step response and the thermal time constant spectrum of GaN HEMTs via time-resolved micro-Raman thermometry. As an expanded form of a recent conference paper [12], we discuss the experimental setup in detail, particularly the elements that determine the temporal resolution by modulating the laser excitation. We show that thermal time constants determined by fitting an exponential decay function to the cooling portion of the periodic pulse response are not characteristic of the device under test (DUT) but are highly dependent on the period and duty cycle of the power dissipation pulses. To more accurately determine a set of thermal time constants for a GaN HEMT, one should measure the temperature difference before and at the end of a power dissipation pulse across a broad range of pulse period durations from ~100 ns to ~$16L_{\text{sub}}^2/\pi^2\alpha_{\text{sub}}$, where $L_{\text{sub}}$ and $\alpha_{\text{sub}}$ are the thickness and thermal diffusivity of the substrate, respectively [22]. This temperature “pseudo-step response” can then be decomposed into a sum of weighted exponential functions whose time constants more accurately characterize the fundamental transient self-heating behavior. For an un gated GaN HEMT on a 500 µm thick SiC substrate, we have demonstrated that a broad range of thermal time constants from ~130 ns to ~3.2 ms contribute to the transient temperature rise. This technique provides an important validation tool for numerical thermal modeling of GaN HEMTs and supports more accurate electro-thermal modeling of these devices with experimentally determined values of the thermal resistances and capacitances in thermal RC networks.

## II. Experimental Setup

Micro-Raman spectroscopy is one of the most popular techniques used to characterize the composition, crystal structure, residual stress, temperature, and other properties of III-nitride semiconductors [23]. Laser light focused on the sample by a microscope objective scatters inelastically to emit (Stokes process) or absorb (anti-Stokes process) optical phonons, and the Raman scattered light is analyzed by a spectrometer equipped with a high sensitivity CCD camera. Each optical phonon mode that is allowed by Raman scattering selection rules appears as a peak whose centroid and linewidth correspond to the frequency and lifetime of that mode, respectively [24]. Due to the fact that phonon frequencies and lifetimes vary with temperature, micro-Raman spectroscopy can be used to measure the local temperature in GaN HEMTs provided that the relationship between Raman peak position and temperature is known by calibration [3]-[5]. The lateral (spot size) and axial (depth) spatial resolution depend on the wavelength of the laser excitation and numerical aperture (NA) of the microscope objective with typical values of ~1 µm and ~5 µm [25]. The temperature resolution, typically ±5 °C or better, depends on the optical characteristics and stability of the spectrometer and the signal to noise ratio of the Raman spectrum. The acquisition time for measuring temperature change based on the change in position and/or linewidth of the Stokes peaks is usually ~1 s, depending on the incident laser power.

Owing to the relatively slow readout time of ~20 ms of CCD cameras used for Raman spectroscopy, traditional micro-Raman thermometry with a continuous wave (CW) laser source cannot capture the rapid temperature rise from ~100 ns to ~1 ms in GaN HEMTs. However, time-resolved micro-Raman thermometry over these short time scales can be achieved by externally modulating the intensity of a high power CW laser to produce a train of optical pulses much shorter than the readout time of the CCD. When synchronized to periodic power dissipation pulses applied to the DUT, Raman scattering and temperature measurement occur only during the optical pulse...
duration even though the CCD is continuously exposed for ~1 s. As the delay time between the beginning of the power dissipation and optical pulses is varied throughout the pulse period, the transient temperature profile is acquired.

Based on this principle, we developed a free space, time-resolved micro-Raman thermography system with a temporal resolution of ~30 ns as shown in Fig. 1. Laser light from a 33612A nm diode pumped solid state (DPSS) laser (Verdi V-10, Coherent) was coupled into an upright microscope (BX41, Olympus) and focused by a 100x, NA = 0.8 microscope objective (LMPPlanFL N, Olympus) onto the DUT. Raman backscattered light ($\tilde{\omega} \cdot z$) was collected along the same optical path, separated from Rayleigh scattered light via a dichroic beamsplitter and longpass edge filter, and analyzed with a ~100 µm diameter spot over which the transient temperature rise and the induced thermoelastic stress in the c-plane according to

$$\Delta \omega_{E_2(\text{high})} = K_{E_2} \sigma + A_{E_2} \Delta T$$

(2a)

$$\Delta \omega_{A_1(\text{LO})} = K_{A_1} \sigma + A_{A_1} \Delta T$$

(2b)

where $d_0$ is the minimum laser beam diameter as it passes through the AOM and $v_s$ is the speed of sound in the crystal [26]. For the TeO$_2$ crystal ($v_s = 4.2 \text{ mm/µs}$) present in the AOM in our system, we achieved a rise time of ~20 ns by focusing the laser light into the AOM with a 400 mm focal length achromatic doublet (L1). As a result, we produced laser pulses as short as 30 ns as measured by the full width at half maximum (FWHM) shown in Fig. 1(b). In a typical experiment, the CW laser power at the input of the AOM was 150 mW and the optical pulse duty cycle was 2.5%, resulting in a time averaged laser power at the sample of ~2 mW due to the 70% diffraction efficiency of the AOM and other losses in the optical path. The actual temporal resolution of a particular measurement with this technique depends on the optical pulse period because the optical pulse width was varied with the period to maintain a constant duty cycle of 2.5% needed to obtain a sufficiently strong Raman signal during the 1 to 2 s CCD exposure times. Despite the high peak laser power of ~80 mW during the optical pulse, we did not observe a significant difference in the GaN Raman peak positions with the time-resolved setup and a steady-state laser power of 6.6 mW, indicating the high peak laser power did not raise the GaN temperature by more than 4 °C.

Electrical power dissipation pulses were applied to the drain of the DUT by means of an in-house pulse IV measurement system consisting of a high precision source measure unit (B2902A, Agilent), a dual channel pulse generator (33612A, Keysight), an external n-MOSFET, and DC probes. The synchronization between the voltage pulses to the drain of the DUT and the optical pulses modulated by the AOM was controlled by the relative delay between the two channels of the pulse generator, which had a temporal resolution of 1 ns. The drain-source voltage ($V_{ds}$) of the DUT and the laser intensity were monitored by an active differential voltage probe and a silicon biased photodetector with a rise time of 1 ns (DET10A, Thorlabs), respectively, to ensure proper timing of the power dissipation and optical pulses. Due primarily to the rise and fall time of the external n-MOSFET in the system, the minimum achievable width of the power dissipation pulses applied to the DUT was ~200 ns.

To illustrate this methodology, we measured the transient temperature rise in an ungated AlGaN/GaN-on-SiC HEMT (10 µm contact spacing, 100 µm width) fabricated by standard procedures [27]. The thicknesses of the GaN buffer and 4H-SiC substrate were 1.3 µm and 500 µm, respectively, with a ~100 nm thick aluminum nitride (AlN) nucleation layer. The GaN HEMT was mounted with 100 µm thick indium solder to a 3 mm thick copper carrier whose backside temperature was maintained at 20.0 ± 0.2 °C with a thermoelectric cooler (TEC, TE-127-1.0-2.5, TE Technology) as shown in Fig. 2(a). To determine the temperature rise of the GaN buffer from the Raman spectrum, we measured the changes in the $E_2$ (high) and $A_1$ (LO) Raman peak positions at a given dissipated power, using the unpowered state as the reference condition as shown in Fig. 2(b) and 2(c). The Raman peak positions depend on both the temperature rise and the induced thermoelastic stress in the c-plane according to

![Fig. 2. (a) Schematic of ungated GaN-on-SiC HEMT under test and (b) GaN $E_2$ (high) and (c) $A_1$ (LO) Raman peak position changes between the unpowered reference state and 20 W/mm dissipated power, 50 µs pulse period, and 50% electrical duty cycle bias condition measured at a delay time of 47.5 µs. The dashed rectangle in (a) indicates the ~0.8 µm diameter spot over which the Raman signal was measured halfway between the contact pads.](image-url)
where \( \Delta \omega \) is the shift in Raman peak position, \( \Delta T = T - T_0 \) is the temperature rise, \( \sigma = (\sigma_{xx} + \sigma_{yy})/2 \) is the average stress in the e-plane, and \( K \) and \( A \) are the stress and temperature coefficients [4]. In the analysis of our experimental data, we used the coefficients reported by Choi et al. [4]. Analyzing the shifts of both the \( E_2 \) (high) and \( A_1 \) (LO) peaks properly decouples the temperature rise from the induced thermoelastic stress without the need for calibration of each sample while additionally providing measurements of the thermoelastic stress. However, (2a) and (2b) cannot capture the effect of the inverse piezoelectric stress and electric field along the c-axis due to the inability of cut off the current in an ungated HEMT [28]. The 100x, NA = 0.8 microscope objective used in our measurements resulted in a laser spot size of \( \approx 0.8 \mu m \) with a depth of field of \( \approx 3.3 \mu m \) [25] such that the temperature and thermoelastic stress values represent the volumetric average value of these quantities over a \( \approx 0.8 \mu m \) cylinder through the depth of the GaN buffer.

III. NUMERICAL MODELING

To support our temperature measurements obtained by time-resolved micro-Raman thermometry, we developed a transient heat conduction model of the GaN HEMT we tested with the finite element analysis (FEA) software COMSOL Multiphysics [29]. The GaN HEMT epitaxial structure was modeled as a 3-D rectangular \((1 \times 1 \text{ mm}^2)\) domain with multiple layers corresponding to the GaN buffer, SiC substrate, and indium solder for which the steady-state temperature distribution at a dissipated power of 20 W/mm is shown in Fig. 3(a). The power dissipation was modeled as a uniform surface heat flux at the top of the GaN buffer between the contacts. For simplicity and computational efficiency, the copper carrier and TEC were not included in the model as they have a negligible impact on the temperature rise at the top of the DUT. Therefore, the temperature at the bottom of the solder layer was set to a uniform value of 20 °C. The side and top surfaces of the die were set to insulated (zero heat flux) due to the negligible effect of natural air convection. Quarter-model symmetry of the structure was also used to reduce the computation time.

The thermal conductivity of GaN and 4H-SiC with their temperature dependence were modeled using the expression

\[
k(T) = k_{300} \left(\frac{300}{T}\right)^n
\]

where \( T \) is the absolute temperature in kelvin, \( k_{300} \) is the thermal conductivity at 300 K, and \( n \) is a dimensionless coefficient. The values of \( k_{300} = 170 \text{ W/m-K} \), and \( n = 1.44 \) for GaN [30]-[31] and \( k_{300,xy} = 490 \text{ W/m-K} \), \( k_{300,zz} = 390 \text{ W/m-K} \), and \( n = 1.49 \) for 4H-SiC [32]-[33] were taken from the literature. The mass density \( \rho_{GaN} = 6087 \text{ kg/m}^3 \) [34], \( \rho_{SiC} = 3220 \text{ kg/m}^3 \) [35]) and specific heat values with their temperature dependencies were also taken from the literature [36]-[37]. The thermal boundary resistance (TBR) at the GaN-SiC interface associated with the AlN nucleation layer was set to a constant value of 5 m²-K/GW, in agreement with recently reported values measured by time-domain thermal reflectance (TDTR) [30]-[31]. The thermal properties of the indium solder were taken as the default values in COMSOL Multiphysics.

Owing to the fact that the two-peak fit method developed by Choi et al. [4] provides both the temperature and average in-plane thermoelastic stress from the shifts of the \( E_2 \) (high) and \( A_1 \) (LO) modes, we also modeled the thermoelastic behavior of the structure to compare modeled and experimental values of the in-plane stress. The elastic constants for GaN, 4H-SiC, and indium were taken from [34]-[35],[38] and the temperature-dependent coefficients of thermal expansion for GaN and 4H-SiC were taken from [4],[39]. The bottom of the indium solder die-attach was set to zero displacement, and all other surfaces, including the top of the GaN buffer, were set to free boundaries (zero stress). The steady-state average of the in-plane stress components \( \sigma_{xx} \) and \( \sigma_{yy} \) calculated with the model at a dissipated power of 20 W/mm is shown in Fig. 3(b). Differences in the coefficients of thermal expansion of GaN and SiC and temperature gradients in the HEMT structure result in compressive thermoelastic stress, as indicated by the negative in-plane stress values in the region of temperature rise.

![Fig. 3](image)

(a) Steady-state temperature rise and (b) in-plane thermoelastic stress distribution modeled in COMSOL Multiphysics for the DUT biased at 20 W/mm, and (c) measured temperature rise for the DUT at with pulse widths of 12.5 \( \mu s \), 25 \( \mu s \), and 50 \( \mu s \) and a 50% electrical duty cycle. Solid lines represent an exponential decay function fitted to the experimental data with the listed time constants. The error bars in (c) represent 95% confidence intervals on the measured temperature rise calculated from the standard deviation of multiple measurements of the Raman peak positions.
IV. RESULTS AND DISCUSSION

A. Periodic Pulse Response

In Fig. 3(c), we show the transient temperature profile for the un gated GaN-on-SiC HEMT described in Section II, biased at 20 W/mm power dissipation with 12.5 µs, 25 µs, and 50 µs pulse widths and a 50% duty cycle. The temperature rise in Fig. 3(c) was calculated from (2a) and (2b), and the error bars represent 95% confidence intervals on the measured temperature rise calculated from the standard deviation of multiple measurements of the $E_2$ (high) and $A_1$ (LO) peak positions, treating the powered and unpowered peak positions as independent measurements. Similar to previous works, the transient temperature profile in Fig. 3(c) rises rapidly during the first ~1 µs interval of the heating phase after the power dissipation pulse begins and continues to rise until the end of the pulse [6]-[11]. The same behavior is observed during the cooling phase in which the temperature rise decreases rapidly then asymptotes. For the 50 µs pulse width condition, we fit an exponential decay function of the form $e^{-t/\tau}$ to the cooling phase and obtained a thermal time constant of $\tau \approx 11.4$ µs, similar to the value of $\tau = 10$ µs reported for an un gated GaN on 300 µm SiC HEMT [6]. However, the arbitrary choice of which data points in Fig. 3(c) to use in the fitting and the different values of $\tau$ obtained from different sets of points motivated us to examine this method of extracting the thermal time constants more closely. Fitting the other measurements with 12.5 µs and 25 µs pulse widths resulted in different time constants with values of 2.34 µs and 4.37 µs.

As shown by classical heat conduction theory, the transient temperature rise of a GaN HEMT due to a step in power dissipation is a sum of weighted exponential functions

$$\Delta T_{\text{step}}(t) = P_{\text{diss}} \sum_{\ell=1}^{\infty} R_\ell \left( 1 - e^{-t/\tau_\ell} \right)$$

$$= P_{\text{diss}} R_{\text{th}} \sum_{\ell=1}^{\infty} r_\ell \left( 1 - e^{-t/\tau_\ell} \right) \quad (4)$$

where $R_\ell$ and $\tau_\ell$ are the weights and thermal time constants, respectively, $P_{\text{diss}}$ is the constant power dissipation level, and $R_{\text{th}}$ is the steady-state thermal resistance [22]. The total weights $R_\ell$ representing resistances in an equivalent Foster circuit can also be specified in terms of the fractional weights $r_\ell$, where $R_\ell = R_{\text{th}}/r_\ell$ and $\sum r_\ell = 1$. Given values of $R_\ell$ and $\tau_\ell$ from modeling or experiment, one can predict the temperature response to any arbitrary power dissipation profile with linear systems theory or an equivalent Foster RC network [42]. Yet, at a fundamental level, time-resolved micro-Raman thermography as it is implemented in this work and others [6]-[11] measures the temperature response of the DUT to a train of $10^5$ to $10^6$ power dissipation pulses $P_{\text{pulse}}(t)$, which can be expressed as

$$\Delta T_{\text{pulse}}(t) = P_{\text{pulse}}(t) \ast \frac{\partial}{\partial t} \left( R_{\text{th}} \sum_{\ell=1}^{\infty} r_\ell \left( 1 - e^{-t/\tau_\ell} \right) \right)$$

where the symbol $\ast$ denotes the convolution operation. Thus, one must exercise caution when attempting to extract values of the thermal time constants from the heating or cooling portion of the temperature profile obtained by time-resolved micro-Raman thermography because it measures the periodic pulse response given by (4) after a dynamic equilibrium is attained, not the step response given by (4) for which the thermal time constants $\tau_\ell$ are defined. Due to the fact that the temperature profiles in Fig. 3(c) do not return to zero at the end of the cooling phase, the decay portion of the curve must be influenced by the step response to the heating phase and previous pulses. To classify any of these values extracted from the measured data in Fig. 3(c) as a thermal time constant defined by (4) would result in erroneous predictions of the temperature response to an arbitrary pulse bias condition.

B. Pseudo-step Response

Due to the inherent limitation that the CCD camera is a slow detector and the Raman scattering process is weak, time-resolved micro-Raman thermometry cannot measure the exact temperature step response given by (4). It may be possible to do so with a single element photodetector and lock-in detection but this alternative implementation of micro-Raman thermography uses the total intensity over a certain spectral window rather than the Stokes peak position to measure temperature [41]. However, the approximate step or “pseudo-step” response can be obtained from a series of periodic pulse response measurements, such as the one shown in Fig. 4(a), at different pulse periods [10]. When the power dissipation duty cycle is low at $\approx 10\%$, the difference between the temperature at the end of the power dissipation pulse of width $t_{\text{pulse}}$ and just before the power dissipation pulse is approximately equal to the temperature step response at $t = t_{\text{pulse}}$. To illustrate this principle, we conducted a series of measurements at 20 W/mm power dissipation with a pulse duty cycle of 12.5% and pulse widths ranging from 250 ns to 12.5 ms from which we derived the temperature pseudo-step response shown in Fig. 4(b). In all cases, the optical duty cycle was fixed at 2.5%. Because the transient drain current $I_d(t)$ and dissipated power $P_{\text{diss}}(t) = V_{ds}(t)I_d(t)$ depend on the channel temperature, which itself changes with the power dissipation pulse width, the drain bias was adjusted for each measurement to maintain the dissipated power at 20 W/mm.

The pseudo-step response measured by micro-Raman thermometry and the step response modeled in COMSOL Multiphysics for the average GaN temperature in Fig. 4(b) show reasonably good agreement across five decades in time from 200 ns to 10 ms. At times shorter than ~10 µs, the experimental temperature values are lower than those predicted by the model, which may be due to uncertainties in the thermal properties of GaN, 4H-SiC, and the AlN nucleation layer to which the modeling results are quite sensitive. The average in-plane thermoelastic stress values shown in Fig. 4(c) agree qualitatively between the measurement and COMSOL Multiphysics model but with the modeled values being 40% to 50% lower than those derived from the changes in Raman peak
This may be an indication that the top surface of the GaN buffer is not fully free to deform, leading to higher compressive in-plane stress in the experiment than in the model under this assumption. As indicated by the dashed curve in Fig. 4(c), setting the contact pad of the ungated GaN HEMT to a fixed (zero displacement) mechanical boundary condition to model the force exerted by the DC probe tip reduces the discrepancy between measurement and model to within ~25%.

Our recent theoretical analysis of 3-D transient heat conduction in GaN HEMTs predicts that the longest thermal time constant present in the step response is given by

$$ \tau_1 \approx \frac{4L_{sub}^2}{\pi^2 \alpha_{zz}} $$

(6)

where $L_{sub}$ and $\alpha_{zz}$ are the thickness and thermal diffusivity of the substrate, respectively [22]. For the 500 µm thick 4H-SiC substrate in our device and $\alpha_{zz} = 1.82 \times 10^4$ m$^2$/s [32],[35],[37], the expression given by (6) predicts a value of $\tau_1 \approx 560$ µs. This value is two orders of magnitude longer than the fitted value of 11.4 µs in Fig. 3(c), indicating that the temperature rise in the die has not reached steady-state at times of 25 to 50 µs despite the apparent asymptotic behavior of the temperature rise. Based on the principle that $1 - e^{-t/\tau_1} \approx 0.98$ at $t = 4\tau_1$, the step-response is expected to approach steady-state at the rise time of

$$ \tau_{rise} \approx 4\tau_1 \approx \frac{16L_{sub}^2}{\pi^2 \alpha_{zz}} $$

(7)

From the experimental temperature pseudo-step response in Fig. 4(b), we observed that the GaN temperature continues to rise after 25 µs until ~2 ms, which agrees with the value of $\tau_{rise} \approx 2.2$ ms calculated with (7). As shown by comparing the modeled average GaN temperature with and without the indium solder die-attach, the die-attach only influences the GaN temperature beyond ~1 ms. Thus, the gradual temperature rise seen in the pseudo-step response from 25 µs to 1 ms is associated with the die alone. For the more typical value of 100 µm thick SiC substrates used in commercial devices, (6) predicts the longest time constant to be $\tau_1 \approx 22$ µs such that the temperature rise associated with the thermal resistance of the die alone saturates at ~80 µs.

C. Thermal Time Constant Spectrum

Given the temperature step response from modeling or experiment, a number of techniques have been developed to extract the time constants $\tau_\ell$ and their fractional weights $\omega_\ell$, including nonlinear regression with multiple exponential functions [5] and deconvolution with a particular weighting function [44]. In this work, we alternatively chose to extract the fractional weights $\omega_\ell$ for a given set of time constants $\tau_\ell$ using the linear least squares regression algorithm LSQLIN available in MATLAB R2016b [45]. Our simple algorithm selected ten time constants per decade spaced logarithmically in time over the timescale of the temperature rise and determined the values of $\omega_\ell$ that minimized the fitting error between a truncated form.
with the die-attach and package material. The extracted time constant of 31.6 µs depends primarily on the thickness and thermal properties of the SiC substrate.

The values of the time constants in Fig. 5(b) obtained from the measured average and modeled peak temperature rise show good agreement, except for the time constant of 35 ns extracted from the modeled peak temperature rise. This is due to the fact that the shortest time measured in the experiment was 200 ns because of the limitations of our pulse IV system. Correspondingly, the weights of the two time constants below 100 ns in Fig. 5(b) extracted from the experimental data are near zero. Owing to the good reproduction of the pseudo-step response in Fig. 5(a) with the thermal time constants in Fig. 5(b), this methodology produces a useful set of thermal time constants for predicting temperature rise, even if the thermal time constants themselves do not correspond exactly to those extracted from the COMSOL Multiphysics model. Clearly a single time constant (2.90 µs for this device) underpredicts and overpredicts the temperature rise at short and long times, respectively, due to its inability to describe 3-D thermal spreading in these devices.

V. CONCLUSIONS

Due to their high power dissipation densities and elevated channel temperatures, GaN HEMTs are a thermally-limited device technology for which thermal modeling and characterization are critical. For a variety of defense, aerospace, and communications applications, GaN-based power amplifiers are operated in pulse mode in which the power dissipation is a strong function of time. In this work, we have developed an experimental methodology for extracting the thermal time constant spectrum of a GaN HEMT using time-resolved micro-Raman thermometry. In contrast to previous works, we measured a broad time constant spectrum across six decades in time from ≈130 ns to ≈3.2 ms associated with aggressive, multidimensional conduction in the die and die-attach. This work provides an important experimental tool for validating transient thermal models of GaN HEMTs and determining thermal resistance and capacitance values for compact electro-thermal modeling via a thermal RC network.

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