

Characterization of GaN-on-SiC wafers using a multi-method laser-based pump-probe technique

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Abstract—Gallium nitride (GaN) high electron mobility transistors (HEMTs) are key components of modern radio frequency (RF) power amplifiers. However, device self-heating negatively impacts both the performance and reliability of GaN HEMTs. Accordingly, laser-based pump-probe methods have been used to characterize the thermal resistance network of epitaxial material stacks that are used to fabricate HEMT structures. However, validation studies of these measurement results at the device level are lacking. In the present work, a GaN-on-SiC wafer was characterized using frequency-domain thermoreflectance and steady-state thermoreflectance techniques. The thermal conductivity of the GaN channel/buffer layer, SiC substrate, and the interfacial thermal boundary resistance at the GaN/SiC interface were determined. Results were validated by performing thermal imaging and modeling of a transmission line measurement (TLM) structure fabricated on the GaN-on-SiC wafer.

Keywords—Frequency-domain thermoreflectance; gallium nitride (GaN); high electron mobility transistor (HEMT); steady-state thermoreflectance; thermal boundary conductance; thermal conductivity; Raman spectroscopy.

I. INTRODUCTION

Gallium nitride (GaN) is a wide bandgap semiconductor that serves as the base material for modern high power and high frequency electronics. GaN high electron mobility transistors (HEMTs) are commercially available; however, GaN HEMTs typically operate under extreme heat flux conditions (>50 kW/cm²) [1], which makes them prone to thermal failure. Therefore, proper thermal management is the key to meet the performance and reliability requirements for today's GaN-based radio frequency (RF) power amplifiers.

Silicon carbide (SiC) is often used as the substrate for GaN HEMTs, which offers a reasonably high thermal conductivity (~ 470 W/mK at room temperature) [2]. The effectiveness of heat removal from the two-dimensional electron gas (2-DEG) channel highly depends on the effective thermal boundary resistance (TBR) or the thermal boundary conductance (TBC; the inverse value of TBR) at the GaN/SiC interface. Several studies have reported the GaN/SiC TBC of AlGaN/GaN HEMTs using laser-based pump-probe methods such as time-domain thermoreflectance (TDTR) and frequency domain thermoreflectance (FDTR). [3]–[6] However, these material-

level thermal characterization results are usually have not been validated at the device-level.

In this work, frequency domain thermoreflectance (FDTR) and steady-state thermoreflectance (SSTR) techniques were used to characterize the thermo-physical properties of a GaN-on-SiC wafer such as the GaN and SiC thermal conductivities as well as the GaN/SiC effective TBC. Nano-particle assisted Raman thermometry was used to measure the channel temperature rise of a transmission line measurement (TLM) structure (which can be viewed as an ungated GaN HEMT) fabricated on this material stack. A 3D thermal model was used to validate the FDTR and SSTR measurement results.

II. EXPERIMENTAL METHODS

Sample Description

The GaN-on-SiC wafer studied in this work consists of a 1.3 μ m thick GaN layer epitaxially grown on a semi-insulating 4H-SiC substrate using a 30 nm thick AlN nucleation layer via metal organic chemical vapor deposition (MOCVD). An 80 nm thick gold transducer was deposited on the surface of the GaN layer to enable thermo-physical property measurement using FDTR and SSTR. Transmission Line Measurement (TLM) structures were fabricated on the GaN-on-SiC wafer to validate the experimental results using nanoparticle-assisted Raman thermometry. The TLMs were designed with a channel width of 100 μ m and channel lengths ranging from 5 to 20 μ m. A schematic of a TLM structure with a channel spacing of 20 μ m is shown in Figure 1.

Thermo-physical Property Measurement

Frequency domain thermoreflectance (FDTR) is an optical pump-probe technique that measures material thermal properties by monitoring the phase lag of thermal waves generated in response to pump laser heating over a range of modulation frequencies. Details of the FDTR setup used in this study can be found in our previous work. [7] The radii of the pump and probe beams were characterized using the knife-edge mode of an optical beam profiler, with the measured beam sizes being 6 μ m and 3.2 μ m, respectively. A sensitivity plot for the GaN-on-SiC wafer studied in this work is shown in Figure 2. In this study, FDTR was used to measure the thermal conductivity

of the GaN layer and the effective TBC at the GaN/SiC interface.

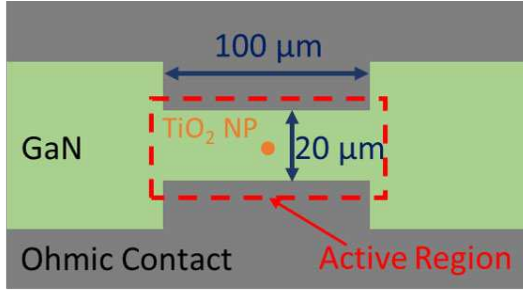


Figure 1: Schematic of the TLM structure and the approximate location of the nanoparticle measured using Raman thermometry (note: the nanoparticle size is not to scale).

Steady-state thermoreflectance (SSTR) is similar to FDTR but measures the surface temperature rise of the material under steady-state (or low frequency) heating. SSTR is more suitable than FDTR for characterizing bulk materials (as compared to thin films) and does not require the knowledge of the density and specific heat of the material. Details of the SSTR setup used in this study can be found in our previous work. [7], [8] In this study, the directionally averaged thermal conductivity of a 4H-SiC substrate was measured using SSTR.

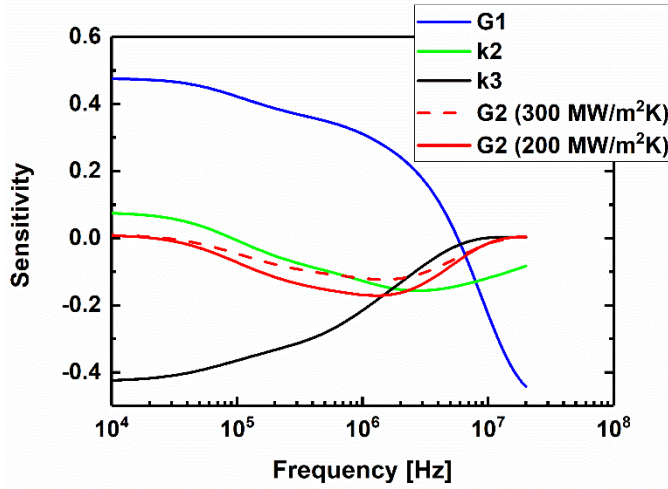


Figure 2: Sensitivity plot for a 1.3 μm thick GaN film measured by FDTR. In the legend, k_2 is the cross plane thermal conductivity of the GaN film. k_3 is the thermal conductivity of the SiC substrate. G_1 and G_2 are the TBCs of the transducer/GaN and GaN/SiC interfaces, respectively.

Nanoparticle-assisted Raman Thermometry

A nanoparticle-assisted Raman thermometry technique [9] was used to measure the surface temperature of the TLM test structures with a 20 μm channel width. Anatase titanium dioxide (TiO_2) nanoparticles with 99.98% purity were deposited on the sample surface to act as a temperature probe. [10], [11] The wavenumber shift of the E_g phonon mode of the TiO_2 nanoparticles was monitored to measure the device surface temperature with a high spatial resolution (~ 200 nm). A photo

of the Raman system and a schematic of the TLM device under test are shown in Figure 4 (a) and (b), respectively.

Modeling

In order to validate the FDTR/SSTR measurement results at the device-level, a 3D finite element analysis (FEA) thermal model was constructed using COMSOL Multiphysics. The thermo-physical properties of the constituent materials and interfaces were adopted from the FDTR and SSTR measurement results. A uniform heat flux corresponding to the operating conditions was applied to the active region of the TLM structure. The bottom of the TLM wafer die was assumed to be at room temperature, similar to the experimental setup. A natural convection thermal boundary condition was applied to all other surfaces.

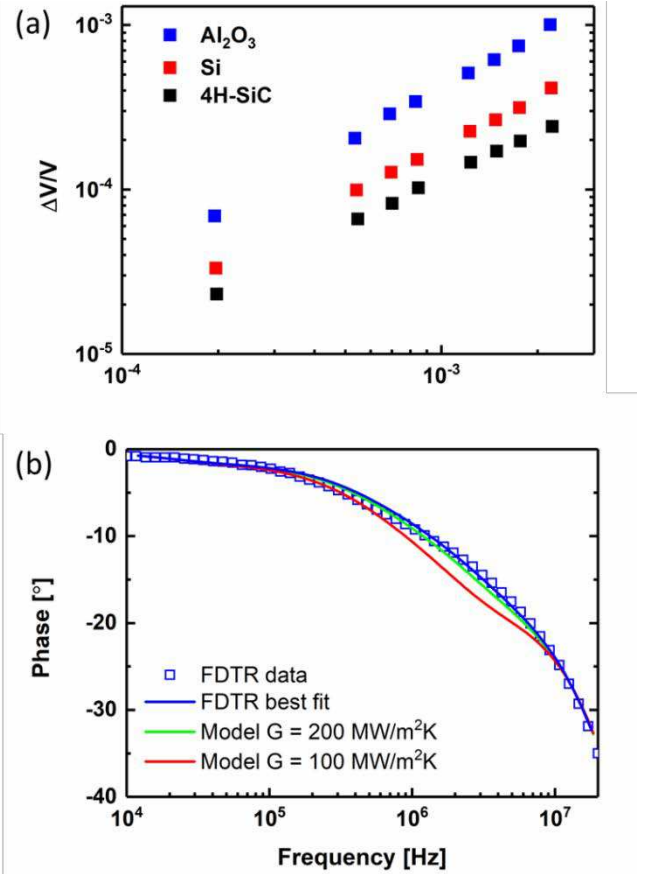


Figure 3: (a) SSTR data used to extract the thermal conductivity of the 4H-SiC substrate, (b) Raw data, the fitting result (solid blue line) for the GaN film measured by FDTR, and the phase models for a GaN/SiC TBC of 100 $\text{MW/m}^2\text{K}$ (solid red line) and 200 $\text{MW/m}^2\text{K}$ (solid green line).

III. RESULTS AND DISCUSSION

The mean value of the thermal conductivity of the 4H-SiC substrate was determined to be 449 W/mK from the SSTR measurements. This measurement was performed on a 4H-SiC wafer without the GaN epitaxial layer. It should be noted that SSTR (raw data shown in Figure 3 (a)) measures a directionally averaged thermal conductivity and the result agrees well with values reported in literature [12]. The measured 4H-SiC thermal

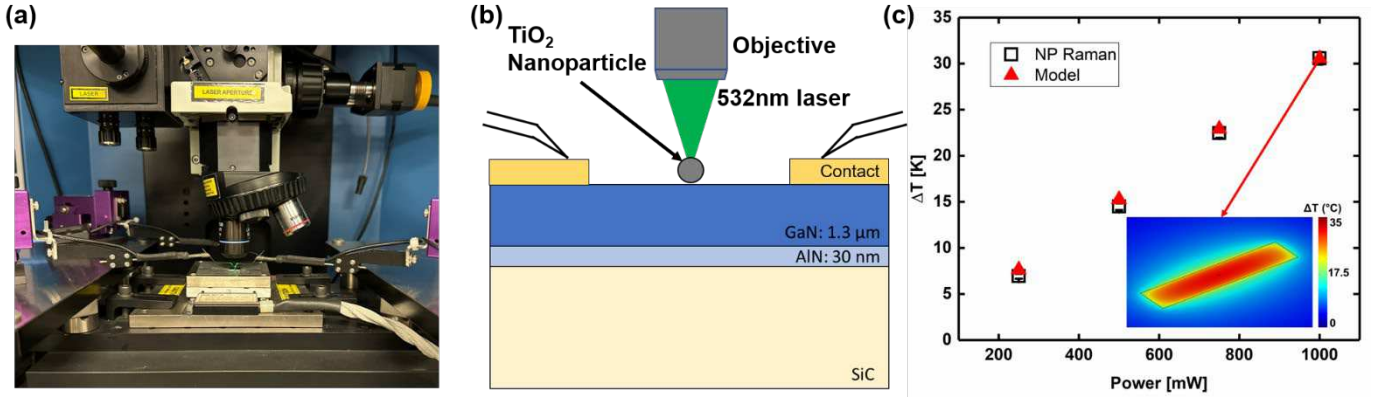


Figure 4: (a) Image of the customized Raman microscope showing the 50× objective, custom probe station, 532 nm wavelength laser illumination, and the device under test. (b) Schematic of the TLM device and the surface temperature measurement; the dimensions are not to scale. (c) Channel temperature rise of a TLM structure measured by nanoparticle assisted Raman thermometry (black squares) and calculated by modeling (red triangles). The insert shows the simulated surface temperature profile for a 1 W power dissipation case.

conductivity was used to extract the effective TBC at the GaN/SiC interface from subsequent FDTR measurements.

The TBC between the Au/GaN (G1), the GaN thermal conductivity (k_2), and the TBC between the GaN/SiC (G2) were fitted simultaneously. The fitting parameters and the fitted results are summarized in Table 1. As shown in Figure 2, the sensitivity to k_2 is low throughout the entire frequency range, and this low sensitivity accounts for the large error bar associated with k_2 . The measured k_2 (166.4 ± 65.5 W/mK) is in good agreement with the GaN film thermal conductivities reported in literature [13]–[15]. The GaN/SiC TBC is best fitted to 300 MW/m²K. As shown in Figure 3 (b), the model deviates from the FDTR measured phase data if the TBC is lower. However, the measurement sensitivity drops significantly and eventually approaches zero at higher GaN/SiC TBCs. This is demonstrated in Figure 2 where the sensitivity to G2 at 200 MW/m²K and 300 MW/m²K are compared. Due to the rapid decrease in the measurement sensitivity, the phase difference at a G2 higher than 300 MW/m²K becomes indistinguishable and therefore determination of the exact value of G2 is difficult.

Table 1: FDTR fitting parameters and results

	Thermal Conductivity (W/mK)	Specific Heat (J/Km ³)	Thickness (nm)	TBC to the next layer (MW/m ² K)
Au	200	2.49×10^6	77.2	44 (fit)
GaN	166.4 ± 65.5 (fit)	3.01×10^6	1314	300 (fit)
SiC	449	2.10×10^6	Infinite	

Nanoparticle-assisted Raman thermometry was used to measure the operating temperature of a TLM structure with a 20 μm channel width fabricated on the same GaN/SiC wafer. The surface temperature results corresponding to a nanoparticle directly in the center of the device active region are shown in Figure 4 (c) along with the modeling results.

The simulated channel temperatures show excellent agreement with the Raman thermometry measurement results, giving confidence to the thermal conductivity and TBC results measured from FDTR and SSSTR. As discussed above, FDTR loses its sensitivity to measure the TBC above 300 MW/m²K. This also translates into a minimal channel temperature rise if the TBC is assumed to be a higher value (simulation results not shown).

IV. CONCLUSION

In this work, thermal characterization of a GaN-on-SiC wafer was performed using SSSTR and FDTR methods. The thermal conductivity of the SiC substrate was characterized using SSSTR (directionally averaged $\kappa = 449$ W/mK). FDTR was used to measure the GaN thermal conductivity (~166 W/mK) and the effective TBC at the GaN/SiC interface (~300 MW/m²K). Nanoparticle-assisted Raman thermometry was used to measure the channel temperature rise of a TLM structure fabricated on this GaN-on-SiC wafer. A 3D thermal model of the TLM was built using the measured thermo-physical properties and the simulated channel temperatures were in excellent agreement with the experimental results. This work demonstrates the validity of laser-based pump-probe methods at the device level and their usefulness for providing key insights into optimizing the thermal performance of GaN device technologies.

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