

Thermal Characterization of Composite GaN Substrates for HEMT Applications

Jungwan Cho¹, Zijian Li¹, Elah Bozorg-Grayeli¹, Takashi Kodama¹, Daniel Francis³, David H. Altman², Felix Ejeckam³, Firooz Faili³, Mehdi Asheghi¹, and Kenneth E. Goodson¹

¹ Department of Mechanical Engineering, Stanford University, Stanford, CA, 94305

² Raytheon Company, Waltham, MA, 02451

³ Group4 Labs, Inc., Fremont, CA, 94539

Abstract: High-power operation of AlGaIn/GaN high-electron-mobility transistors (HEMTs) requires efficient heat removal through the substrate. GaN composite substrates including high-thermal-conductivity substrates such as SiC and diamond are promising, but these composite substrates require careful attention to thermal resistances at GaN-substrate interfaces. We report on thermal characterization of GaN-on-SiC and GaN-on-diamond substrates using a combination of picosecond time-domain thermoreflectance (TDTR) and DC Joule heating techniques.

Keywords: High-electron-mobility transistors (HEMTs); Gallium nitride; Silicon carbide; diamond; picosecond pump-probe thermometry; thermal conductivity; thermal interface resistance.

Introduction

High-electron-mobility transistors (HEMTs) based on AlGaIn/GaN are promising for high-power, high-frequency transistors and optoelectronic devices due to their high electron sheet charge densities and high electrical breakdown fields [1]. High-power operation exceeding 40 W/mm has been recently reported for a GaN-on-SiC configuration [2]. But localized device-level self-heating limits the peak power density and degrades device reliability [3]. The low thermal conductivity of the GaN buffer layer and the high thermal boundary resistances (TBRs) at interfaces in some composite substrates impede efficient heat dissipation from the heated device region.

Past work estimated the thermal resistance at the GaN-substrate interface using either optical transient interferometric mapping [4], [7] or Raman thermometry [4]-[6]. These measurements did not determine the GaN thermal conductivity but rather assumed a value for this property as an input to the data fitting procedure. While the relevant through-plane thermal conductivity of representative GaN films has been measured accurately using the 3ω method [8], this property varies strongly with fabrication details. The community needs more accurate data and measurement strategies for the GaN conductivity and interface resistance, and these properties should be captured simultaneously in the same composite substrate targeted for HEMT applications.

This paper combines picosecond pump-probe time-domain thermoreflectance (TDTR) with electrical techniques involving nanopatterned bridges to characterize GaN-on-SiC and GaN-on-diamond substrates. The primary goal is accurate measurements of the resistance between GaN regions and the high thermal conductivity substrate as well as the intrinsic GaN thermal conductivity.

Samples and Experimental Methods

The GaN-on-SiC samples consist of three thicknesses of GaN on 4H-SiC wafers (Table 1). The GaN epilayer was grown on a SiC substrate by metal-organic chemical vapor deposition (MOCVD) followed by etching to the target GaN thickness. An AlN nucleation layer (~28 nm) between the GaN buffer and the SiC substrate minimizes lattice mismatch. An evaporated Al layer (50 nm thick) serves as the transducer for picosecond TDTR measurements. Figure 1 includes representative transmission electron microscopy (TEM) images for confirming sample dimensions.

Table 1. Geometries and thicknesses for GaN-on-SiC substrates

Sample	Al Thickness [nm]	GaN Thickness [nm]	AlN Thickness [nm]
A	53.9 ± 3.6	884 ± 8	27.8 ± 0.9
B	56.5 ± 2.9	1271 ± 8	26.9 ± 1.2
C	53.8 ± 3.0	1562 ± 6	26.2 ± 1.7

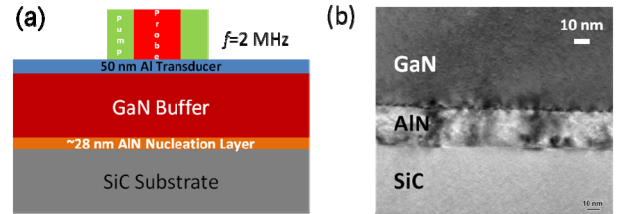


Figure 1. (a) Cross sectional schematic drawing of the GaN-on-SiC samples. (b) Representative cross-sectional TEM image of sample A near the GaN-SiC interface.

Figure 2 illustrates one of two GaN-on-diamond substrates used in this study. The AlGaIn/GaN heterostructure was grown on a Si substrate by MOCVD. Following the MOCVD growth, this wafer was front-side mounted to a sacrificial carrier, and the Si substrate was etched away.

The remaining AlGaIn/GaN layers were attached to polycrystalline diamond using a disordered adhesion layer of ~50 nm as described previously [9]. The resulting epitaxial layer is composed of GaN buffer/AlGaIn transition layer/adhesion layer/CVD diamond substrate from the top. Evaporated Al layers of 51 nm serve as the transducer for picosecond TDTR measurements on both samples. Cross-sectional transmission electron microscopy (TEM) images confirm the sample dimensions (Table 2).

Table 2. Geometries and thicknesses for GaN-on-Diamond substrates

Sample	GaN Thickness [nm]	AlGaIn Thickness [nm]	Adhesion layer Thickness [nm]
A	828	142	3–42
B	848	269	38–55

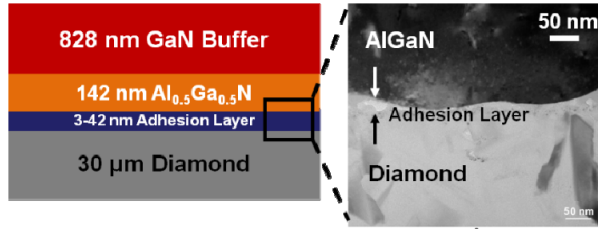


Figure 2. Cross-sectional schematic drawing of the GaN-on-diamond substrate (Sample A) with representative cross-sectional TEM near the adhesion layer

Picosecond TDTR thermometry is well-established for determining near-surface thermal conductivities and interface resistances in multilayer thin film structures [10]–[12]. A passively mode-locked Nd:YVO4 laser with an 82 MHz repetition rate generates 9.2 ps pulses at wavelength $\lambda = 1064$ nm. A beamsplitter separates these pulses into pump and probe components. The frequency-doubled pump beam, modulated by an electro-optic modulator (EOM) for lock-in detection, deposits heat in the metal transducer. The probe beam is temporally delayed from the pump via a linear delay stage, and the beam determines the reflectivity of the transducer film. For small temperature rises, the reflected intensity measures the surface temperature decay over 3.5 ns [13]. A 3-D radial symmetric heat diffusion solution for the multilayer stack is fitted to the normalized temperature decay to extract the properties of films beneath the metal transducer [10]. We validate system accuracy by extracting a thermal conductivity of 1.38 W/mK for a SiO₂ calibration sample.

DC Joule heating thermometry helps investigate and verify the thermal properties of the GaN-substrate interface. We fabricated Au nanoheaters with widths varying from 50nm to 5μm on top of the sample stack using the e-beam photolithography. The electrical thermometry captures the temperature by measuring the electrical resistance change

in the nanoheaters. Different heater widths spatially confine the heat to a certain depth into the sample stack, yielding optimal sensitivity to different layers and interfaces. The temperature rise is measured by monitoring the voltage across the heater bridge. Since the temperature coefficient of resistivity (TCR) of Au is dependent on film thickness partly due to the electron scattering at film boundaries, a calibration is performed before each measurement. Data is fitted using a multilayer heat diffusion model to determine the thermal properties of the underlying material.

Results and Discussion

GaN-on-SiC substrate: Picosecond TDTR measurements are used to characterize the three GaN-SiC substrates with GaN thicknesses near 1 μm. We are unable to resolve the intrinsic resistance of the AlN (R_{AlN}) and the thermal boundary resistances (TBRs) at its boundaries ($TBR_{GaN-AlN}$ and $TBR_{AlN-SiC}$). Rather, we lump the three contributions into one single interface resistance: $R_{GaN-SiC} = TBR_{GaN-AlN} + R_{AlN} + TBR_{AlN-SiC}$. The thermal penetration depth of the modulated pump beam is approximately 2.1 μm in GaN, which is larger than the GaN layer thicknesses. As a result, the measurement is sensitive both to $R_{GaN-SiC}$ as well as k_{GaN} . We use multiple GaN thicknesses to extract the GaN conductivity and the interface resistance independently under the assumption that the properties do not vary strongly among the three samples.

We compare two methods for interpreting the thermal decay traces from the TDTR data: 1) a simultaneous fit of the TDTR temporal traces for all three samples, and 2) extrapolation of the thermal resistances determined separately for the three samples. The first method optimizes the analytical thermal decay curves for all three samples to determine k_{GaN} and $R_{GaN-SiC}$, with all other properties held constant. For the second method, we consider a single effective layer with conductivity k_{eff} that lumps k_{GaN} and $R_{GaN-SiC}$ together. For thermal resistors in series, $L_{GaN}/k_{eff} = L_{GaN}/k_{GaN} + R_{GaN-SiC}$, which shows that the stack resistance (L_{GaN}/k_{eff}) increases linearly with GaN thickness (L_{GaN}). A plot of stack resistance versus GaN thickness reveals k_{GaN} to be the inverse of the slope, and $R_{GaN-SiC}$ to be the y-intercept.

Figure 3 illustrates the two approaches described above. Figure 3(a) shows the simultaneous fitting approach for the representative thermal traces. Using this method, we find $k_{GaN} = 157 \pm 11$ W/mK and $R_{GaN-SiC} = 4.2 \pm 0.6$ m²K/GW at room temperature. Variations in the thickness of the Al transducer determine the error bars. Uncertainties due to multiple spot measurements lie within the error bars reported above. The initial time behavior (at time scales below ~1 ns) of the thermal decay traces determine the Al/GaN TBRs, which vary between 8.9 and 13.3 m²K/GW for the three samples. The difference in the Al-GaN TBRs can be due to the different levels of oxidation,

contamination and roughness of the samples [11]. Regarding the second approach, a plot of stack resistance versus GaN thickness is depicted in Fig. 3(b). Using this method, we obtain $k_{\text{GaN}} = 182 \pm 33$ W/m/K and $R_{\text{GaN-SiC}} = 3.6 \pm 1.6$ m²K/GW within error bars of the previous technique. These GaN conductivities are comparable with existing published data [8].

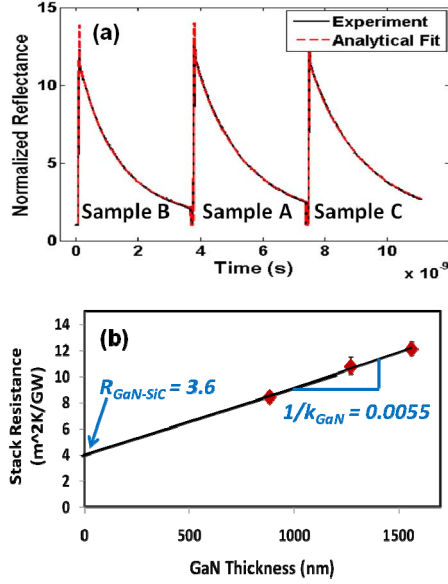


Figure 3. (a) Simultaneous curve fits for all samples with representative thermal traces at room temperature. (b) Plot of stack resistance versus GaN thickness.

GaN-on-diamond substrate: Picosecond TDTR measurements are performed on the two GaN-on-diamond substrates (Sample A and B) to extract the thermal resistances between the GaN and diamond. The thermal resistances between the GaN and diamond ($R_{\text{GaN-Diamond}}$) consist of two components: the $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ intrinsic resistance (R_{AlGa}) and the thermal resistance of the adhesion layer (R_{ADH}): $R_{\text{GaN-diamond}} = R_{\text{AlGa}} + R_{\text{ADH}}$. Here, the intrinsic resistance of the adhesion layer and the TBRs at its boundaries are lumped into a single resistance (R_{ADH}).

The measurements aim at extracting the thermal resistances of the adhesion layer (R_{ADH}) in both samples. To accurately determine these values, all other thermal parameters must be known. The electrical thermometry determines the thermal conductivity of the GaN buffer layer. The narrow heaters (50–80nm) confine the heat within the top layers, so that the temperature rise in the heater is most sensitive to the thermal conductivity of the GaN. This measurement yields $k_{\text{GaN}} = 90$ W/mK. For the thermal conductivity of the $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ film, we take our data for a 550 nm-thick $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ layer from an independent study ($k_{\text{AlGa}} = 16.6$ W/mK at room temperature) [14]. The diffuse mismatch model (DMM) [15] predicts the GaN/AlGa TBR to be 0.8 m²K/GW.

Table 3 summarizes all the measured values in both samples. Picosecond TDTR measurements determine that the thermal resistances of the adhesion layer range from 17 to 42 m²K/GW. Further, we find the TBRs between the Al transducer and GaN buffer layer ($R_{\text{Al-GaN}}$) to be 10.6 ± 1.2 m²K/GW for sample A and 10.2 ± 1.2 m²K/GW for sample B. The uncertainty bars in these results are due to the effects of the Al transducer thickness ($d_{\text{Al}} = 51.0 \pm 3.5$ nm). We perform DC Joule heating measurements on the same samples to verify the TDTR results. Wider heaters generate heat that penetrates deep into the layer stack and capture the adhesive thermal resistance. The measured thermal resistances at room temperature agree with the TDTR results within uncertainties.

Table 3. Thermal resistance of adhesion layer for GaN-on-Diamond substrates

Measurement technique	$R_{\text{ADH, A}}$ [m ² K/GW]	$R_{\text{ADH, B}}$ [m ² K/GW]
Picosecond TDTR	27 ± 10	31 ± 11
DC Joule heating	25 ± 11	29 ± 12

Summary and Conclusions

The thermal resistances between the GaN and substrate ($R_{\text{GaN-substrate}}$) are measured for both GaN-on-SiC and GaN-on-diamond substrates, using a combination of picosecond TDTR and DC Joule heating techniques. Table 4 summarizes all the measurements for both types of samples. For the GaN-on-SiC samples, picosecond TDTR measurements determine the intrinsic GaN conductivity (k_{GaN}) and the GaN-SiC thermal interface resistance ($R_{\text{GaN-SiC}}$). For the GaN-on-diamond samples, the thermal resistances of the adhesion layer (R_{ADH}) in two samples are extracted using picosecond TDTR. Independent DC Joule heating measurements on the same samples confirm the TDTR results. Utilizing k_{AlGa} taken from our previous measurement, the GaN-diamond thermal interface resistances ($R_{\text{GaN-diamond}}$) are determined to be 36 ± 12 m²K/GW for sample A and 47 ± 15 m²K/GW for sample B.

Table 4. Thermal resistances between GaN and substrate for both GaN-on-SiC and GaN-on-diamond substrates

Sample	k_{GaN} [W/mK]	$R_{\text{GaN-substrate}}$ [m ² K/GW]
GaN-on-SiC samples	157–182	4–5
GaN-on-diamond, sample A	90	36 ± 12
GaN-on-diamond, sample B	90	47 ± 15

Thermal conductivities of the GaN buffer layers in these composite substrates range between 90 and 182 W/mK with the lower values obtained on diamond composite substrates. For the samples characterized, the GaN-diamond thermal interface resistances are relatively higher

than those of the GaN-on-SiC samples. It is expected that the GaN on diamond thermal interfaces will improve with further development. Recent simulation work has shown that HEMT-on-diamond with a GaN-diamond thermal interface resistance of $< 30 \text{ m}^2\text{K/GW}$ can outperform HEMT-on-SiC even with zero GaN-SiC thermal interface resistance in terms of device temperature rise [16]. Therefore, a further reduction in the GaN-diamond thermal interface resistance should be achieved and should eventually enhance cooling of HEMT-on-diamond devices. Future work is focusing on detailed characterization of the transitional layers.

Acknowledgements

This work was supported by the DARPA Microsystems Technology Office (MTO) through Air Force contract FA8650-10-7044. J. Cho is supported by Samsung Scholarship, Z. Li is supported by Stanford Graduate Fellowship, and E. Bozorg-Grayeli is supported by National Defense Science and Engineering Graduate (NDSEG) Fellowship.

References

1. Mishra, U. K., P. Parikh, and Y. F. Wu, "AlGaIn/GaN HEMTs-An Overview of Device Operation and Applications," *Proceedings of the IEEE*, vol. 90, no. 6, pp. 1022-1031, Jun. 2002.
2. Wu, Y. F., M. Moore, A. Saxler, T. Wisleder, and P. Parikh, "40-W/mm double field-plated GaN HEMTs," *Proc. IEEE DRC Conf. Dig.*, p.151, 2006.
3. Meneghesso, G., G. Verzellesi, F. Danesin, F. Rampazzo, F. Zanoni, A. Tazzoli, M. Meneghini, and E. Zanoni, "Reliability of GaN highelectron-mobility transistors: State of the art and perspectives," *IEEE Trans. Device Mater. Rel.*, vol. 8, no. 2, pp. 332-343, Jun. 2008.
4. Kuzmik, J., S. Bychikhin, D. Pogany, C. Gaquiere, E. Pichonat, and E. Morvan, "Investigation of the thermal boundary resistance at the III-nitride/substrate interface using optical methods," *J. Appl. Phys.*, vol. 101, no. 5, pp. 054 508.1-054 508.6, Mar. 2007.
5. Sarua, A., H. Ji, K. P. Hilton, D. J. Wallis, M. J. Uren, T. Martin, and M. Kuball, "Thermal boundary resistance between GaN and substrate in AlGaIn/GaN electronic devices," *IEEE Trans. Electron Devices*, vol. 54, no. 12, pp. 3152-3158, Dec. 2007.
6. Manoi, A., J. W. Pomeroy, N. Killat, and M. Kuball, "Benchmarking of Thermal Boundary Resistance in AlGaIn/GaN HEMTs on SiC Substrates: Implications of the Nucleation Layer Microstructure," *IEEE Electron Device Lett.*, vol. 31, pp. 1395-1397, Dec. 2010.
7. Kuzmik, J., S. Bychikhin, D. Pogany, E. Pichonat, O. Lancry, C. Gaquiere, G. Tsiakatouras, G. Deligeorgis, and A. Georgakilas, "Thermal characterization of MBE-grown GaN/AlGaIn/GaN device on single crystalline diamond," *J. Appl. Phys.*, vol. 109, pp. 086106.1-086106.3, 2011.
8. Liu, W. and A. A. Balandin, "Temperature dependence of thermal conductivity of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ thin films measured by the differential 3ω technique," *Appl. Phys. Lett.*, vol. 85, no. 22, pp.5230 - 5232, Nov. 2004.
9. Francis, D., F. Faili, D. Babic, F. Ejeckam, A. Nurmikko, H. Maris, "Formation and characterization of 4-inch GaN-on-diamond substrates," *Diam. Rel. Mat.*, vol. 19, pp. 229-233, Feb. 2010.
10. Cahill, D. G., "Analysis of heat flow in layered structures for time-domain thermoreflectance," *Rev. Sci. Instrum.*, vol. 75, no. 12, pp. 5119-5122, Nov. 2004.
11. Reifenberg, J. P., K. W. Chang, M. Panzer, S. B. Kim, J. A. Rowlette, M. Asheghi, H. S. P. Wong, and K. E. Goodson, "Thermal Boundary Resistance Measurements for Phase-Change Memory Devices," *IEEE Electron Device Letters*, vol. 31, no. 1, pp. 56-58, Jan. 2010.
12. Cho, J., E. Bozorg-Grayeli, D. H. Altman, M. Asheghi, and K. E. Goodson, "Low Thermal Resistances at GaN-SiC Interfaces for HEMT Technology," *IEEE Electron Device Letters*, in press.
13. Ujihara, K., "Reflectivity of metals at high temperature," *J. Appl. Phys.*, vol. 43, no. 5, pp. 2376-2383, May 1972.
14. Cho, J., Z. Li, E. Bozorg-Grayeli, T. Kodama, D. Francis, F. Ejeckam, F. Faili, M. Asheghi, and K. E. Goodson, "Thermal Characterization of GaN-on-Diamond Substrates for HEMT Applications," *ITHERM 2012*, 2012, San Diego.
15. Bellis, L. D., P. E. Phelan, and R. S. Prasher, "Variations of acoustic and diffuse mismatch models in predicting thermal-boundary resistance," *J. Thermophys. Heat Transf.*, vol. 14, no. 2, pp. 144-150, Apr.-Jun. 2000.
16. Li, Z., M. Asheghi, and K. E. Goodson, "Impact of Composite Substrates on Near Junction Self Heating of High Electron Mobility Transistors," *Electron. Lett.*, under review.