

THERMAL CONDUCTIVITY, ANISOTROPY, AND INTERFACE RESISTANCES OF DIAMOND ON POLY-AIN

Elah Bozorg-Grayeli, Zijian Li, Vincent Gambin, Mehdi Asheghi, and Kenneth E. Goodson

Department of Mechanical Engineering

Stanford University

Stanford, CA, USA, 94305

Phone: (480) 223-3993

Fax: (650) 723-7657

Email: ebozorgg@stanford.edu

ABSTRACT

Due to their high thermal conductivity, diamond substrates are seen as a way to minimize the thermal resistance present in High Electron Mobility Transistor (HEMT) structures based on GaN. Single-crystal AlN transition layers facilitate the growth of high quality GaN on diamond, but such layers may increase the total thermal resistance of the composite substrate. This manuscript measures the thermal conductivity and interface resistance of a 1.4 μm diamond film on a polycrystalline AlN substrate using picosecond time-domain thermoreflectance (TDTR) and nanosecond thermoreflectance. Varying beam widths are used to extract the thermal conductivity anisotropy of the diamond film.

KEY WORDS: Aluminum nitride, diamond, High Electron Mobility Transistors (HEMT), Thermal Boundary Resistance (TBR), thermal conductivity, Time-Domain Thermoreflectance (TDTR)

NOMENCLATURE

A	area, m^2
C	volumetric heat capacity ($\text{J m}^{-3} \text{K}^{-1}$)
d	thickness (nm)
f	frequency (10^6 Hz)
k	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
R	thermal resistance ($10^{-9} \text{ m}^2 \text{K W}^{-1}$)

Subscripts

diam	diamond film
sub	substrate
tran	transition layer
x	lateral
z	cross-plane

INTRODUCTION

High electron mobility transistors (HEMT) based on GaN semiconducting layers offer a variety of challenges related to fabrication, design, and thermal management. An AlGaIn-GaN heterojunction creates a highly conductive 2-dimensional electron gas (2DEG) confined between semiconducting layers [1]. This high electron mobility layer arises due to band bending at the AlGaIn-GaN interface, where the conduction band briefly dips below the Fermi level [2]. By depositing source and drain structures contacting the 2DEG and a gate structure on top of the AlGaIn layer, one can manipulate the

electron layer in a similar manner to Si-based field effect transistors (FET). However, such transistors are capable of faster response times and higher AC operating frequencies than Si-based FETs [3]. The wide bandgap and high breakdown voltage of the AlGaIn-GaN heterojunction allow greater power to be pumped through the device [4], and the high thermal conductivity substrates facilitate thermal management of such large power densities [3]. This ability to operate faster at higher power than Si-based FETs makes HEMT devices attractive for applications involving amplification of radio-frequency and microwave radiation [3, 5].

Due to the large power densities present in HEMT devices, thermal management is a critical issue. Because the substrate is a key contributor to the total thermal resistance, considerable attention is paid to substrate selection. The current preferred substrate is SiC, with diamond substrates being proposed to allow for even greater power densities. A transition layer, based on AlN, usually sits between the HEMT structure and the substrate in order to promote the growth of high-quality GaN buffer films (Fig. 1) [6].

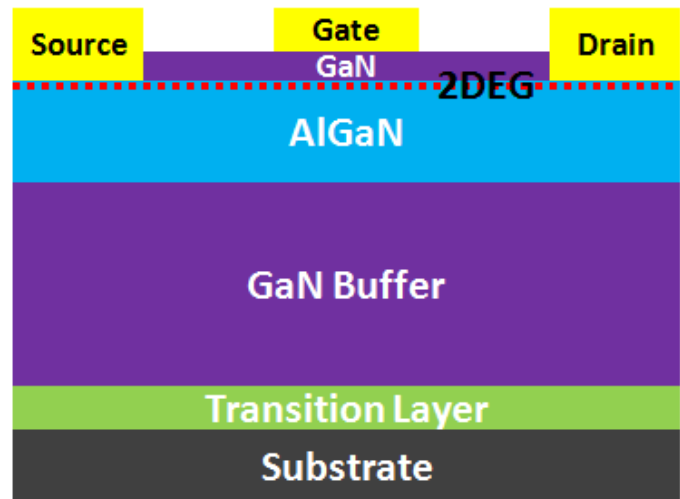


Fig. 1 A representative HEMT structure based on the AlGaIn/GaN heterojunction.

Since the buffer layer and substrate are high quality crystalline films with much lower dislocation and impurity density than

the transition layer, it is likely that the dominant thermal resistances in the HEMT system will be that of the disordered low-quality buffer region near the transition layer, and the buffer-substrate interface. The latter resistance, expressed as:

$$R_{tran} = R_{GaN-tran} + \frac{d_{tran}}{k_{tran}} + R_{tran-sub} \quad (1)$$

includes the GaN-transition layer thermal boundary resistance ($R_{GaN-tran}$), the intrinsic thermal resistance of the transition layer due to the thickness (d_{tran}) and thermal conductivity (k_{tran}) of the transition layer, and the transition layer-substrate thermal boundary resistance ($R_{tran-sub}$).

The thermal boundary resistance (TBR) components of R_{tran} are due to two main factors. First, the acoustic impedance mismatch between the two materials at an interface produces an effect similar to Snell's Law, where phonons transmit or reflect with a probability determined by the mismatch [7, 8]. The Diffuse Mismatch Model expresses this transmissivity as [8]:

$$\alpha_{1 \rightarrow 2} = \frac{\sum_j c_{2,j}^{-2}}{\sum_j c_{1,j}^{-2} + \sum_j c_{2,j}^{-2}} \quad (2)$$

where $\alpha_{1 \rightarrow 2}$ is the probability a phonon will transmit from material 1 to material 2 and $c_{i,j}$ is the sound speed in material i for polarization j . Using this result, one can calculate TBR using the simplified relation [9]:

$$R_{1 \rightarrow 2} = \left(\frac{\alpha_{1 \rightarrow 2}}{12} c_{1,d}^3 \sum_j c_{1,j}^{-2} \right)^{-1} C_1(T)^{-1} \quad (3)$$

where $c_{1,d}$ is the polarization-averaged sound velocity in material 1 and $C_1(T)$ is the temperature-dependent volumetric heat capacity. Second, the presence of impurities, defects, or small grains near the interface may significantly reduce the mean free path of nearby energy carriers. This increases the thermal resistance beyond the value expressed in Equation (3).

The transition layer resistance complicates the discussion of minimizing the thermal resistance between the HEMT device and the cooling solution. As mentioned before, diamond substrates, with thermal conductivities reported to be on the order of $2000 \text{ W m}^{-1} \text{ K}^{-1}$ [10], are seen as an appropriate replacement for existing SiC substrates. However, if the total resistance of the transition layer is large enough, it can outweigh the thermal resistance improvements offered by using a diamond substrate.

For example, let us compare the thermal resistances of a hotspot on a GaN/SiC or GaN/Diamond structure using a simple heat spreading analysis. In this approach, we assume a hotspot of varying width (w) and length (L) on top of the GaN/Substrate stack. The spreading resistance for such a hotspot on an arbitrary substrate is given by [11]:

$$R_{spreading} = \frac{1}{S k_{sub}} = \frac{1}{2 \sqrt{\frac{wL}{\pi}} k_{sub}} \quad (4)$$

where S is a shape factor determined by the heating geometry and k_{sub} is the thermal conductivity of the substrate. Between the GaN and substrate layers is a thermal boundary resistance. This TBR impedes heat flow and affects the healing length of the hotspot within the GaN layer [12]:

$$L_h = \sqrt{d_{GaN} k_{GaN} \left(\frac{d_{sub}}{k_{sub}} + R_c \right)} \quad (5)$$

where d_{GaN} is the thickness of the GaN layer, k_{GaN} is the thermal conductivity, and R_c is the TBR between the GaN and substrate. This healing length dictates the area over which heat diffuses from the interface into the substrate. Using this information, we find the total thermal resistance experienced by the hotspot:

$$R_{total} = \frac{1}{2 \sqrt{\frac{wL}{\pi}} k_{GaN}} + \frac{R_c}{(w + 2L_h)L} + \frac{1}{2 \sqrt{\frac{(w + 2L_h)L}{\pi}} k_{sub}} \quad (6)$$

The first term in this sum will be the same for SiC and diamond substrates. Comparisons of different GaN-substrate combinations will focus on the last two terms.

For example, consider a hotspot generated by a HEMT gate with length 100x its width (Fig. 2). For transition layer resistances above $5 \text{ m}^2 \text{ K/GW}$, we see that the combined substrate and boundary thermal resistance for device widths on the order of 10 nm is larger for diamond than for SiC. This situation would arise if: 1) more transition layer material is required to handle the lattice mismatch between diamond and GaN, 2) the mismatch in acoustic properties between the two films produces a much larger thermal boundary resistance, or 3) the defect density within the transition layer is higher due to mismatch stresses.

Although work exists in measuring R_{tran} for SiC substrates [13-16], no such measurements have been performed for diamond. This paper presents picosecond time-domain thermoreflectance (TDTR) and nanosecond thermoreflectance (NTR) measurements of a diamond on poly-AlN system. From these measurements, we extract the intrinsic thermal conductivity of the diamond, the anisotropy of the diamond thermal conductivity, and the thermal interface resistance (TIR) experienced by diamond on poly-AlN. The presence of a low-quality layer AlN layer near the interface prevents us from referring to the diamond-AlN resistance as a TBR, since some degree of intrinsic conduction is involved. Comparing the diamond-AlN TIR to the transition layer resistance measured in GaN-SiC systems, we posit that $R_{tran-sub}$ and the

intrinsic transition layer resistance may be the most significant contributor to R_{tran} for GaN on diamond.

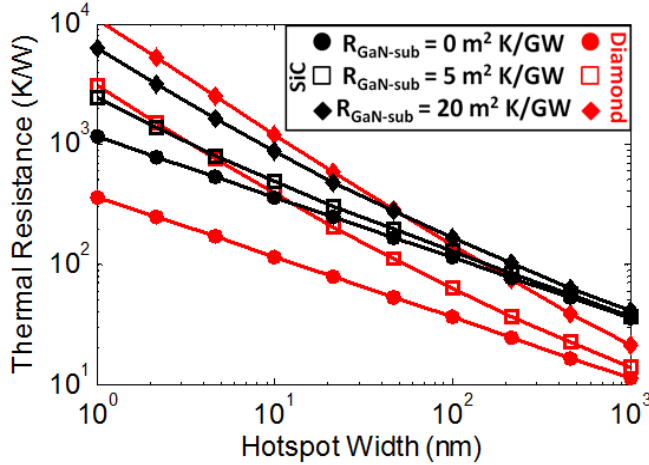


Fig. 2 Substrate and boundary thermal resistance experienced by HEMT gates of varying width with fixed aspect ratio. The simulated sample consists of 1000 nm GaN on diamond/SiC.

EXPERIMENTAL METHOD

Extracting the thermal properties of a thin diamond film is not a trivial task. Since these films may have conductivities on the order of $2000 \text{ W m}^{-1} \text{ K}^{-1}$ [10, 17], it becomes difficult to separate their intrinsic thermal resistances from the boundary resistances [18]. In order to access the intrinsic resistance of the diamond film independently of the TBR, we must confine our measurement to the film region of interest. As the regime map in Figure 3 demonstrates, there are several temporal measurement regimes capable of accessing the thermal properties of a wide range of diamond film thicknesses. In order to obtain both total film resistance and individual TBRs, we used a combination of nanosecond- and picosecond- scale optical techniques.

NTR and picosecond TDTR operate on significantly different time scales, but utilize the same physical principle to measure the temperature decay of a heated metal transducer on a stack of thin film materials. In both cases, a pump beam pulse rapidly heats the metal transducer. A separate probe beam interrogates the reflectivity of the transducer as a function of time after the pulse. Since the reflectivity of the transducer scales linearly with temperature, the reflected probe beam signal acts as a thermometer for the metal film [19].

The critical difference between the two techniques arises from their vastly different timescales. Since the temperature decay from a NTR pulse takes place over several μs , it can be captured using only the bandwidth of a single photodetector [20]. However, the thermal decay from picosecond TDTR is only a few ns long, so such a technique is not viable. Instead, we split the pulse from a single Nd:YVO₄ laser into a pump and probe component. The pump travels along a fixed path to the sample. A linear delay stage controls the path length of the probe pulse, which strikes the sample at a controlled time after the pump beam [21]. Further, by amplitude modulating the pump beam and using a lock-in to measure the probe beam

component at that modulation frequency, we separate the thermoreflectance component of the beam from the total reflected signal.

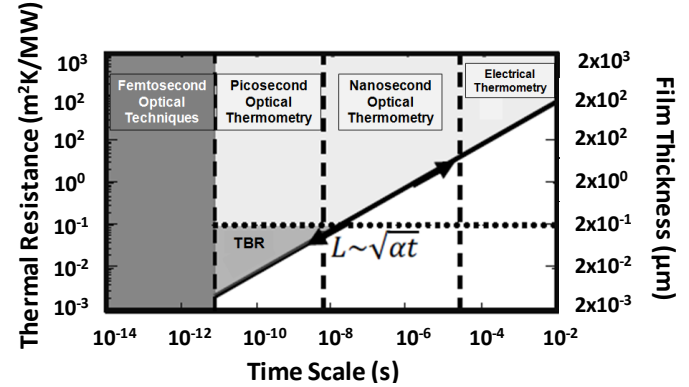


Fig. 3 Regime map of accessible thermal resistances for various time-scale measurements. The shaded regions indicate the resolvable range of thermal resistance for that particular technique. In the case of our $1.4 \mu\text{m}$ diamond films, we may use nanosecond and picosecond optical thermometry.

We fit for the thermal properties of the materials beneath the transducer layer using a multilayer heat diffusion model [22]. Since the NTR pump beam is much larger than the thickness of the diamond film, thermal spreading is negligible, and conduction is effectively 1-D. However, since the picosecond TDTR pump beam is of the same order as the film thickness, we utilize a 2-D radially-symmetric model [23]. Figure 4 demonstrates the TDTR result for a calibration sample consisting of aluminum on SiO₂ on silicon.

In simulating heat diffusion through multilayer stacks, it is important to consider whether the thermal conductivity anisotropy of the film significantly affects the measurement. When the thickness of the film is of the same order as the width of the heating source, such spreading effects are non-negligible. Further, the thickness-dependent columnar grain structure of diamond films impedes the mean free path (MFP) of phonons in the lateral direction, reducing the lateral thermal conductivity [10, 18]. Since the $1/e^2$ pump beam waist in our experiment is $10 \mu\text{m}$, only 7x the thickness of the film, thermal spreading effects are non-negligible. To counteract this, we use microscope objectives of varying magnification to control the width of our pump and probe beams (Fig. 5). This allows us to tune the sensitivity of the measurement to lateral thermal conduction. The wider pump beam data gives the cross-plane thermal conductivity of the sample. We use this result with the thinner pump beam data to determine the lateral thermal conductivity of the sample. Combining both of these results with NTR measurements of total film resistance uniquely extracts the cross-plane and lateral diamond thermal conductivity, the Al-diamond TBR, and the diamond-AlN TIR.

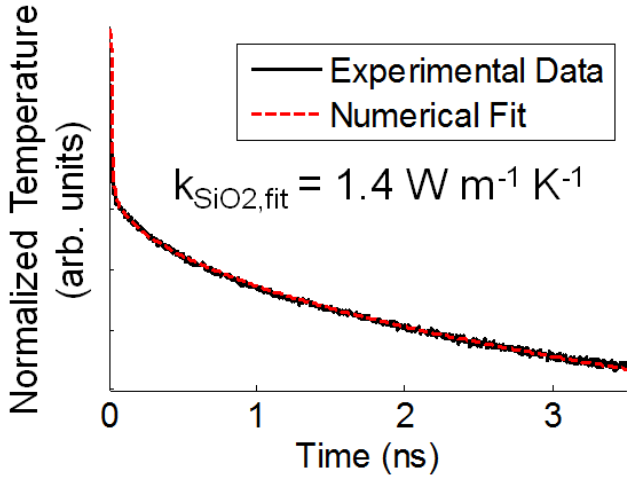


Fig. 4 Characteristic thermal decay curve and numerical fit for a sample consisting of Al on SiO₂ on Si. The numerical fit reveals gives a SiO₂ thermal conductivity of 1.4 W m⁻¹ K⁻¹.

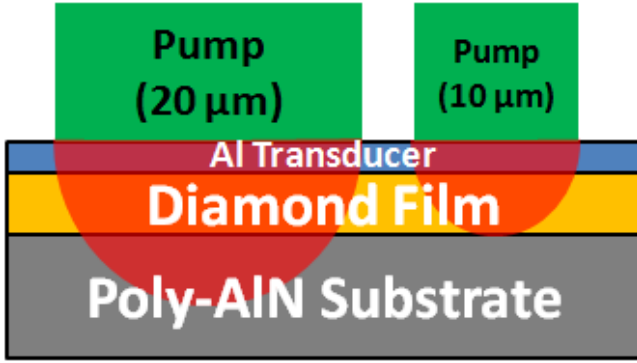


Fig. 5 Wider heat sources are less sensitive to thermal spreading resistance in the diamond film. As such, varying pump beam widths can control the measurement sensitivity to lateral thermal properties.

SAMPLE PREPARATION

The sample design goal for this experiment was to mimic the diamond-AlN interface in a HEMT device while placing that interface within the thermal penetration depth of the measurement technique. Further, in order to access the thermal properties of the diamond film, we required direct contact between the transducer and diamond layers. The samples therefore consisted of a poly-AlN substrate which had been chemically-mechanically polished (CMP) to create a smooth growth surface. This resulted in a ~ 100 nm damaged AlN region at the interface. Subsequently, 1.4 and 1.7 μm of diamond were CVD-grown on the AlN substrate (Fig. 6). The picosecond TDTR sample (1.4 μm diamond) received a 50 nm Al transducer, while the NTR sample (1.7 μm diamond) received a significantly thicker transducer.

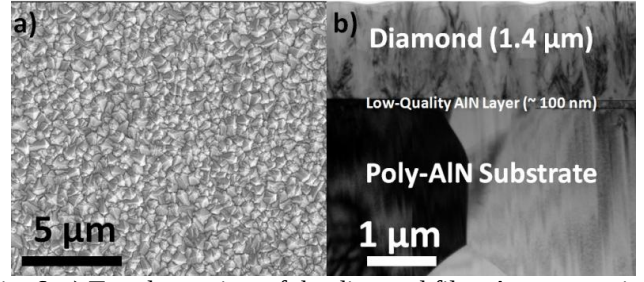


Fig. 6 a) Top-down view of the diamond film. Average grain width is ~ 0.5 μm. b) Cross-sectional view of the diamond on poly-AlN sample.

RESULTS AND DISCUSSION

From the NTR measurements, we extracted the total effective cross-plane thermal conductivity (k_{eff}) of the diamond film. This value, 57.4 W m⁻¹ K⁻¹, includes both the intrinsic resistance of the diamond and the diamond-AlN TIR. Since the timescale of the measurement is much longer than the characteristic decay length of the diamond film, we are incapable of separating the intrinsic and boundary resistance components. Instead, this result determines a range of possible values for intrinsic diamond thermal conductivity (k_{diam}) and diamond-AlN TIR ($R_{AlN-diam}$). Using $R_{eff} = d_{diam}/k_{eff}$ as the total thermal resistance of the film, k_{diam} and $R_{AlN-diam}$ are related by:

$$k_{diam} = \frac{d_{diam}}{R_{eff} - R_{AlN-diam}} \quad (7)$$

Figure 7 plots the value of $R_{AlN-diam}$ as a function of k_{diam} .

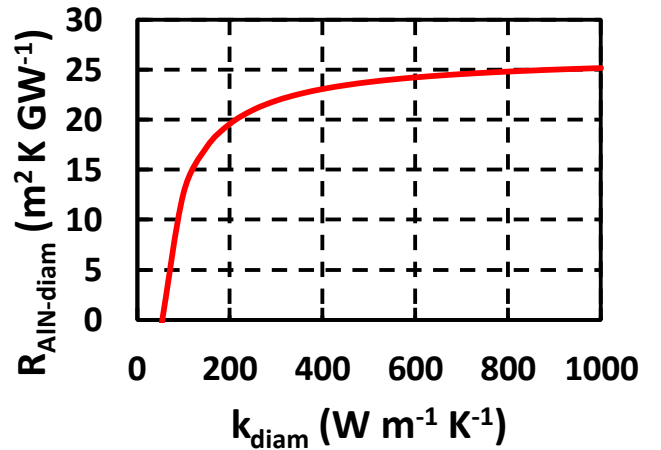


Fig. 7 Nanosecond thermoreflectance reveals the total cross-plane thermal resistance of the diamond film to be 26.6 m² K GW⁻¹. This plot demonstrates the range of possible diamond thermal conductivities and AlN-diamond TIRs (obtained using Equation 7) given this data.

Although the NTR data does not allow separation of these two resistances, the results form a constraint for the picosecond TDTR results. In this case, we numerically fit for k_{diam} and $R_{AlN-diam}$, using Equation 7 to link the two values. This model, in combination with the varying beam waist data, yields $k_{diam} = 300 \pm 40$ W m⁻¹ K⁻¹ in the cross-plane direction, with an

anisotropy of $k_x/k_z = 0.75 \pm 0.05$. Further, we find $R_{Al-diam} = 10.4 \pm 0.5 \text{ m}^2 \text{ K GW}^{-1}$ and $R_{AIN-diam} = 19.7 \pm 1.0 \text{ m}^2 \text{ K GW}^{-1}$ (Fig. 8). The uncertainty bars in these results are due to the existence of multiple possible combinations of k_{diam} and $R_{AIN-diam}$ which fit the picosecond TDTR data and satisfy the constraint of Equation (7). Past measurements on the thermal properties of diamond films on silicon showed similar results for diamond-substrate TBRs [18] and intrinsic diamond thermal conductivity [10].

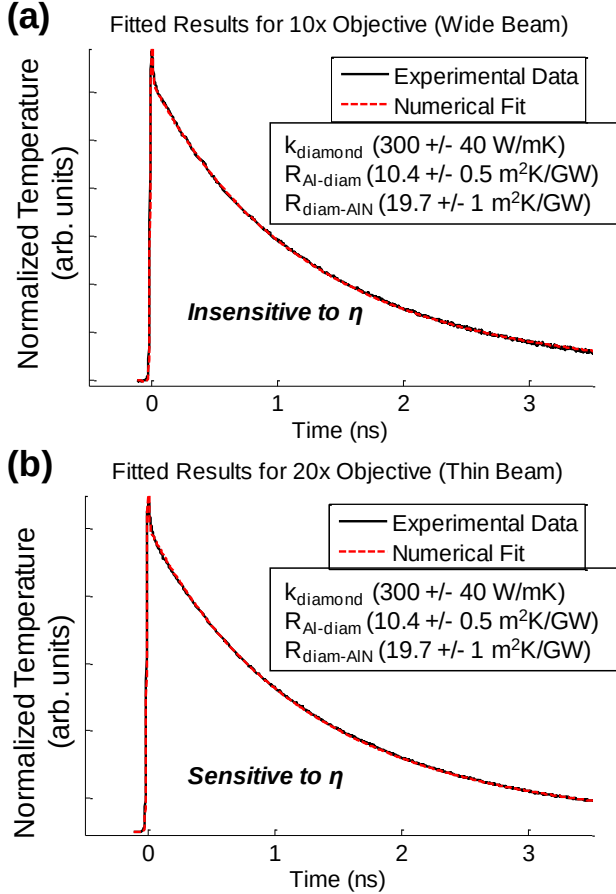


Fig. 8 Thermal decay traces for the diamond on AlN samples using (a) a 10x objective and (b) a 20x objective. The fitted results are shown in the boxes below the legends. From these results, we find the diamond thermal conductivity anisotropy to be $\sim 0.75 \pm 0.05$.

Since the diamond layer is significantly thicker than the low-quality AlN layer, and the separation between the transducer and AlN layers is quite large, the heat capacitance of the diamond overwhelms that of the AlN layer. While the high diamond thermal conductivity prevents this from significantly impeding the measurement's sensitivity to the properties of the AlN film, it does make it difficult to separate the diamond-AIN TBR from the intrinsic resistance of the low-quality AlN film. However, by comparing our results to similar work for GaN on SiC, we can evaluate the performance of a GaN-diamond interface [13-15].

Manoi et al report the thermal interface resistance trend between GaN and SiC, with room temperature results ranging from 5 to 30 $\text{m}^2 \text{ K/GW}$. Specifically, for an AlN nucleation layer of 70 nm thickness between GaN and SiC, room temperature TIR ranges from 20 to 25 $\text{m}^2 \text{ K GW}^{-1}$ [15]. They further demonstrate that this resistance scales with nucleation layer defect density. The diamond-AIN TIR measured here is similar to the results of [15]. Although our structure lacks the GaN-transition layer TBR, this value is likely significantly smaller than what is reported here.

This diamond-AIN TIR contributes significantly to the total transition layer resistance. There are three potential causes for this large resistance: grain boundary scattering, defect scattering, and acoustic impedance mismatch. First, the grain size in CVD diamond depends strongly on the thickness of the film [18]. Near the diamond growth surface is a layer of very small diamond grains, upon which the larger columnar grains grow. The presence of the CMP-damaged layer further impedes the growth of larger grains. These small grains significantly reduce the phonon mean free path, resulting in a thin region of low thermal conductivity near the interface. Since the region is thin compared to the total thickness of the diamond film, the increased scattering resistance appears as a TBR. Second, the high defect density of the CMP-damaged region significantly reduces the mean free path of phonons in transition layer. Finally, the phonon transmissivity at an interface depends on the relative acoustic properties of the two films [8]. Since the CMP step significantly damaged the AlN near the diamond-AIN interface, the resulting 100 nm layer is likely far more compliant than the original poly-AIN substrate. As a result, the sound velocity mismatch between the transition layer and diamond will be high. This significantly lowers phonon transmissivity at the interface and increases TBR.

In order to improve the performance of the diamond substrate, we must address the above contributions to TIR. We can reduce all three scattering sources through the use of single-crystal AlN nucleation layers. Grain boundary scattering, defect scattering, and reduced phonon transmissivity all stem from the presence of the damaged AlN layer. A high-quality, single-crystal AlN film would provide a better growth surface for the diamond film, improve the phonon mean free path within the transition layer, and enhance phonon transmissivity at the diamond-AIN interface.

SUMMARY AND CONCLUSION

The performance of diamond in HEMT applications depends on both the intrinsic and interface thermal resistances of the substrate. Several phenomena govern the interface resistance, including grain boundary scattering, defect scattering, and acoustic impedance mismatch. If these three components contribute to a transition layer resistance in excess of 5 $\text{m}^2 \text{ K/GW}$, diamond loses the advantage over traditional SiC substrates. We quantified the diamond-AIN TIR using time-domain and transient thermoreflectance techniques, and determined the TIR to be $\sim 19.7 \text{ m}^2 \text{ K/GW}$. Although this value exceeds the limit for which diamond is more effective

than SiC, higher quality growth surfaces should significantly reduce the diamond-AlN TIR, potentially making such substrates optimal choices for HEMT thermal management.

ACKNOWLEDGMENTS

The authors would like to thank their colleagues at Northrop Grumman for their invaluable input on this work. This research was made with Government support under and awarded by DoD, Air Force Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG) Fellowship, 32 CFR 168a.

REFERENCES

- [1] M. Asif Khan, A. Bhattacharai, J. N. Kuznia, and D. T. Olson, "High electron mobility transistor based on a GaN/Al_xGa_{1-x}N heterojunction," *Applied Physics Letters*, vol. 63, pp. 1214-1215, 1993.
- [2] B. Jogai, "Influence of surface states on the two-dimensional electron gas in AlGaIn/GaN heterojunction field-effect transistors," *Journal of Applied Physics*, vol. 93, pp. 1631-1635, 2003.
- [3] U. K. Mishra, P. Parikh, and W. Yi-Feng, "AlGaIn/GaN HEMTs-an overview of device operation and applications," *Proceedings of the IEEE*, vol. 90, pp. 1022-1031, 2002.
- [4] W. Yi-Feng, D. Kapolnek, J. P. Ibbetson, P. Parikh, B. P. Keller, and U. K. Mishra, "Very-high power density AlGaIn/GaN HEMTs," *IEEE Transactions on Electron Devices*, vol. 48, pp. 586-590, 2001.
- [5] Y. F. Wu, B. P. Keller, S. Keller, D. Kapolnek, P. Kozodoy, S. P. Denbaars, and U. K. Mishra, "High power AlGaIn/GaN HEMTs for microwave applications," *Solid-State Electronics*, vol. 41, pp. 1569-1574, 1997.
- [6] C. Mion, J. F. Muth, E. A. Preble, and D. Hanser, "Thermal conductivity, dislocation density and GaN device design," *Superlattices and Microstructures*, vol. 40, pp. 338-342, 2006.
- [7] I. M. Khalatnikov and I. N. Adamenko, "Theory of the Kapitza Temperature Discontinuity at a Solid Body-liquid Helium Boundary," *Soviet Journal of Experimental and Theoretical Physics*, vol. 36, 1973.
- [8] E. T. Swartz and R. O. Pohl, "Thermal boundary resistance," *Reviews of Modern Physics*, vol. 61, p. 605, 1989.
- [9] L. D. Bellis, P. E. Phelan, and R. S. Prasher, "Variations of Acoustic and Diffuse Mismatch Models in Predicting Thermal-Boundary Resistance," *Journal of Thermophysics and Heat Transfer*, vol. 14, pp. 144-120, 10/29/1999 2000.
- [10] J. E. Graebner, S. Jin, G. W. Kammlott, J. A. Herb, and C. F. Gardinier, "Large anisotropic thermal conductivity in synthetic diamond films," *Nature*, vol. 359, pp. 401-403, 1992.
- [11] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 5 ed.: John Wiley and Sons, 2001.
- [12] K. E. Goodson, M. I. Flik, L. T. Su, and D. A. Antoniadis, "Prediction and Measurement of Temperature Fields in Silicon-on-Insulator Electronic Circuits," *Journal of Heat Transfer*, vol. 117, pp. 574-581, 1995.
- [13] A. Sarua, J. Hangfeng, 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 Transactions on Electron Devices*, vol. 54, pp. 3152-3158, 2007.
- [14] J. Kuzmik, S. Bychikhin, D. Pogany, C. Gaquière, E. Pichonat, and E. Morvan, "Investigation of the thermal boundary resistance at the III-Nitride/substrate interface using optical methods," *Journal of Applied Physics*, vol. 101, p. 054508, 2007.
- [15] A. Manoi, 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," *Electron Device Letters, IEEE*, vol. 31, pp. 1395-1397.
- [16] G. J. Riedel, J. W. Pomeroy, K. P. Hilton, J. O. Maclean, D. J. Wallis, M. J. Uren, T. Martin, U. Forsberg, A. Lundskog, A. Kakanakova-Georgieva, G. Pozina, E. Janzen, R. Lossy, R. Pazirandeh, F. Brunner, J. Wurfl, and M. Kuball, "Reducing Thermal Resistance of AlGaIn/GaN Electronic Devices Using Novel Nucleation Layers," *Electron Device Letters, IEEE*, vol. 30, pp. 103-106, 2009.
- [17] G. A. Slack, "Thermal Conductivity of Pure and Impure Silicon, Silicon Carbide, and Diamond," *Journal of Applied Physics*, vol. 35, pp. 3460-3466, 1964.
- [18] K. E. Goodson, O. W. Käding, M. Rösler, and R. Zachai, "Experimental investigation of thermal conduction normal to diamond-silicon boundaries," *Journal of Applied Physics*, vol. 77, pp. 1385-1392, 1995.
- [19] K. Ujihara, "Reflectivity of Metals at High Temperatures," *Journal of Applied Physics*, vol. 43, pp. 2376-2383, 1972.
- [20] M. A. Panzer, G. Zhang, D. Mann, X. Hu, E. Pop, H. Dai, and K. E. Goodson, "Thermal Properties of Metal-Coated Vertically Aligned Single-Wall Nanotube Arrays," *Journal of Heat Transfer*, vol. 130, p. 052401, 2008.
- [21] M. A. Panzer, M. Shandalov, J. A. Rowlette, Y. Oshima, C. Yi Wei, P. C. McIntyre, and K. E. Goodson, "Thermal Properties of Ultrathin Hafnium Oxide Gate Dielectric Films," *Electron Device Letters, IEEE*, vol. 30, pp. 1269-1271, 2009.
- [22] A. Feldman, "Algorithm for Solutions of the Thermal Diffusion Equation in a Stratified Medium with a Modulated Heat Source," *High Temperatures - High Pressures*, vol. 31, pp. 293-298, 1999.
- [23] D. G. Cahill, "Analysis of Heat Flow in Layered Structures for Time-Domain Thermoreflectance," *Review of Scientific Instruments*, vol. 75, pp. 5119-5122, 2004.

