Characterization of the Thermal Conductivity of CVD Diamond for GaN-on-Diamond Devices

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***Abstract* — Diamond films grown by chemical vapor deposition have the potential to improve the thermal management and reliability of AlGaN/GaN high electron mobility transistors. The integration of CVD diamond with GaN involves the nucleation and growth of diamond films on GaN which induces a vertical gradient in thermal conductivity of the diamond and can result in bulk properties that depend greatly on growth conditions. Thus accurate characterization of the thermal conductivity of CVD diamond, especially the lower conductivity near the growth interface is needed to assess the impact on AlGaN/GaN HEMTs. In this work, we present measurements of the thickness dependence of CVD diamond with thicknesses ranging from 5 to 13.8 μm in addition to bulk diamond substrates using time domain thermoreflectance. Measurements were made on the same samples in two different laboratories which showed excellent correlation between the measurements. The diamond properties were then utilized in a thermal model of a 10 finger AlGaN/GaN HEMT to predict the impact of device junction temperature. Compared to a device made on SiC operating at 5 W/mm, a junction temperature reduction of 30-40% was seen when using CVD diamond and the same device size**

***Index Terms* —Thermal conductivity, diamond, GaN, thermal management.**

I. Introduction

Gallium nitride (GaN) based high electron mobility transistors (HEMTs) have proven to have great potential for RF devices and power electronics [1,2]. The development and fabrication of AlGaN/GaN HEMTs on SiC substrates been the primary focus in industry in order to produce reliable transistors. In spite of the high thermal conductivity of SiC substrates, these devices are still limited to DC power densities on the order of 7-10 W/mm considering a maximum junction temperature of 200°C. This limitation is a direct result of the thermal resistance imparted by the SiC which must be addressed in order to push the limits of the technology. Recently, the use of CVD diamond in GaN HEMTs has shown promise in increasing the power densities of these devices without increasing the junction temperature[3]. However, the integration of CVD diamond into GaN HEMTs through growth on the backside of the GaN buffer layer results in the nucleation and columnar growth of diamond grains with large gradients in thermal conductivity in the film [4]. Measurements of the thermal conductivity of 1 μm diamond films have shown thermal conductivity values that can be less than 100 W/mK while bulk films can have thermal conductivities >2000 W/mK [5]. Thus, this strong gradient in thermal conductivity along with thermal boundary resistance between the diamond and GaN are expected to play a role in the success of using CVD diamond as a thermal management solution in GaN. However, accurate characterization of the thickness dependence of the thermal conductivity in order to analyze the impact on the performance of GaN-on-Diamond devices.

In this work, we utilize TDTR to measure the thermal conductivity of CVD diamond films grown on Si substrates from 5 – 13.8 μm in thickness by Element Six. Additional measurements were also made on bulk samples ranging from 300 – 550 μm in thickness also grown by Element Six. The surface of the samples were polished to a surface roughness less than 30 nm rms to facilitate thermal conductivity measurements. Measurements were performed at two different laboratories in order to correlate thermal conductivity measurements and investigate some sources of variability. The results were then used to estimate the impact on the thermal response of 10 finger AlGaN/GaN HEMTs with SiC and diamond with a vertical gradient in thermal conductivity.

II. Experimental Methods

We use time-domain thermoreflectance (TDTR), a well-established optical pump-probe method to measure the thermal conductivity of diamond-on-silicon and bulk diamond samples. Samples were coated with a thin film of aluminum (80-100 nm thick) that acts as an opto-thermal transducer. Two different setups at Stanford and Georgia Institute of Technology (hereafter, GT) were employed to make measurements. The setup at Stanford uses a Nd:YVO_4 532/1064 nm pump/probe system with a ~ 10 ps pulse-width, 82 MHz repetition rate, and pump and probe 1/e2 spot diameters of 10 um and 6 um, respectively. The GT setup is built around a Ti: Sapphire laser with 400/800 nm pump/probe wavelengths, ~ 100 fs pulse-width, 80 MHz repetition rate, and pump/probe diameters in the 10-80 um range. The probe beam is delayed relative to the pump using a mechanical delay stage, giving pump-probe delays of up to 3.6 ns at Stanford, and 7.5 ns at GT. The pump beam is amplitude modulated at frequencies between 1-10 MHz to enable lock-in detection of the reflected probe intensity. This modulation also imposes a thermal probing length-scale that determines the measurement sensitivity to thermal properties at various depths within the sample stack. The data consist of the in-phase and out-of-phase voltage signals measured by the lock-in amplifier, Vin and Vout, as a function of time delay. A thermal model fits the amplitude (quadrature of Vin and Vout) or the ratio (-Vin/Vout) to a solution of the multilayered heat conduction equation to extract the unknown properties of interest. For these samples, the unknown quantities are the isotropic conductivity of the diamond ($k_{z,D} = k_{r,D}$), and the thermal boundary resistance at the Al/diamond interface (TBR_{Al-D}). For the 5-13.9 um diamond-on-silicon samples, the TBR at the diamond/Si interface (TBR_{D-Si}) is fixed at 15 m^2-K/GW, although we are not very sensitive to this parameter.

III. Results

We first describe results from the bulk diamond samples (see Table I), comparing values obtained at Stanford and GT, with those measured using the Laser Flash method by Element Six. Stanford utilizes the amplitude data to extract the Al/diamond thermal boundary resistance and the ratio data to extract the diamond thermal conductivity. GT uses the ratio data to extract both parameters using multi-frequency fitting. The data show that the thermal conductivity ranges from close to 700 W/m-K up to 2200 W/m-K. Some of the samples were boron doped which resulted in a reduced thermal conductivity due to point defect phonon scattering. Overall, we observe good agreement between the data reported by Stanford and GT within experimental uncertainty, showing the consistency of the TDTR method. In addition, the results show good agreement with the Flash Diffusivity method. The error bars for the TDTR data shown in Table I come from standard deviations from multi-spot measurements. Owing to intrinsically high thermal conductivity of bulk diamond samples, the TDTR data have relatively large uncertainties, especially for the sample with a thermal conductivity over 2000 W/m-K where the signal to noise ratio for the sample decreases due to the lower sample heating and lower change in thermoreflectance signal.

TABLE I
SUMMARY OF BULK DIAMOND DATA

Diamond thickness (μm)	Stanford conductivity (W/m-K)	GT conductivity (W/m-K)	Laser Flash (W/m-K)
534	706 (+/-18%)	650 (+/-10%)	714 (+/-7%)
511	1642 (+/- 21%)	1470 (+/-9%)	1519 (+/-7%)
449	N/A	2200 (+/-20%)	2137 (+/-7%)
352	1830 (+/- 33%)	1940 (+/-15%)	1927 (+/-8%)

Table II provides a summary of the data taken on the 5-13.8 μm thick diamond on silicon samples. The data measured by Stanford and GT are in good agreement with each other (Figure 1 and Figure 2), to within the error bars of the measurements. The data show an increase in thermal conductivity with increasing film thickness, going from approximately 700 W/m-K at 5 μm to approximately 1360 W/m-K at 13.8 μm. For this growth recipe, the bulk thermal conductivity for films >100 μm is reported by Element Six to be 1500 W/m-K. The rapid increase in thermal conductivity at lower film thicknesses is attributed to the expansion in grain size moving away from the nucleation surface. This expansion tapers off and results in only a modest increase in thermal conductivity with increasing film thickness.

While good agreement was observed between GT and Stanford, additional measurements were performed to understand the variations. To investigate the effects of spot-size and spot-to-spot material variations on the measured data, Stanford and GT performed measurements on the 5 μm thick diamond on Si sample using a coordinate system to ensure that very similar locations were measured by both teams. While Stanford used pump/probe diameters of 10/6 um, GT used pump/probe diameters of 10/4.2 um. A coordinate system was setup with 9 spots chosen on a 3x3 grid, with a spacing of 12.5

um in both directions. Over 9 spots, Stanford measured a conductivity of 689 +/- 33 W/m-K, while GT measured 666 +/- 40 W/m-K. The error bars represent standard errors ($2\sigma/N^{0.5}$, where N = 9) in the data. The agreement between these values is better than 3.5 %, showing that spot-spot variations can be accounted for in an accurate manner, if spots are chosen as close to each other as possible by multiple teams.

TABLE II
SUMMARY OF DIAMOND/SILICON DATA

Diamond thickness (um)	Stanford conductivity (W/m-K)	GT conductivity (W/m-K)
5	694 (+/- 4%)	712 (-21%/+30%)
8.2	1115 (+/- 9%)	1155 (-20%/+32%)
11.8	1232 (+/- 19%)	1421 (-12%/+16%)
13.9	1382 (+/- 10%)	1362 (-11%/+12%)

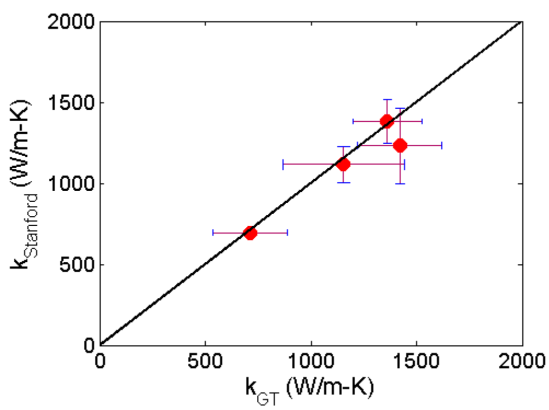

Figure 1. Comparison between thermal conductivities measured by Stanford and GT for 5-13.9 um diamond-on-Si samples

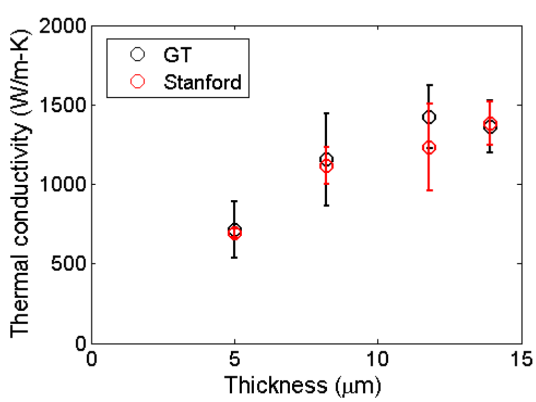

Figure 2. Thermal conductivity plotted versus film thickness, as measured by Stanford and GT, for diamond-on-Si samples.

IV. Modeling Impact on Devices

The impact of CVD diamond on the thermal performance of AlGaN/GaN HEMTs was modeled using ANSYS. To develop the thermal model of the device, first the thermal response of a 10 finger AlGaN/GaN HEMT on SiC was characterized using Raman Spectroscopy (Figure 3). The device contained a 1 μm GaN buffer layer on top of a 100 μm thick SiC substrate. The channel width was 180 μm, a gate-to-drain spacing of 3 μm. The gate-to-gate spacing was 30 μm between the first two pair of gates which were separated from the next pair by 70 μm as seen in Figure 3. The device was mounted onto a copper block that was attached to a thermal stage held fixed at 30°C. Raman temperature measurements were made using a Renishaw InVia microRaman system using a 488 nm Ar+ laser with a 50x objective. The devices were powered up to 7 W/mm power density using DC biasing. An ANSYS model was developed to take into account the entire stack of the device which was validated by correlating with the experimental temperatures of the center channel and the channel at the edge of the device as shown in Figure 3.

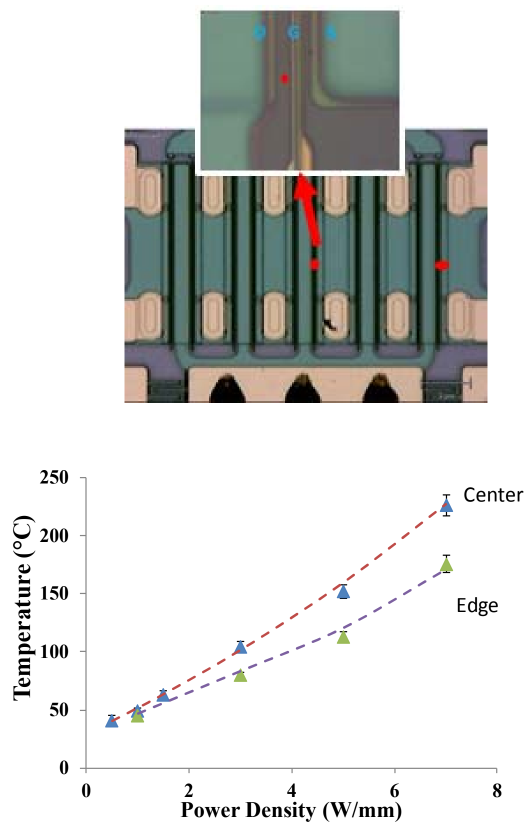

Figure 3. Picture showing the 10 finger AlGaN/GaN HEMT and location of Raman measurement (red dots) and the comparison of the ANSYS model (dashed lines) to the experimental data (symbols).

After validating the thermal model, the SiC layer was replaced with a 100 µm thick diamond layer to determine the influence of diamond on the temperature rise in the device. The diamond layer was integrated with a thermal boundary resistance of 27 m^{2}K/GW between the diamond and GaN which was measured on a separate diamond on GaN sample made by Element Six. A theoretically low TBR of 3 m^{2}K/GW was also considered to bound the potential response. The diamond was implemented in two different ways. First, a bulk thermal conductivity of 1500 W/mK with an anisotropy ratio of 2:1 was considered. Next, the gradient in thermal conductivity based on the measured in Figure 2 along with an anisotropy ratio of 2:1 was considered. The results are shown in Figure 4 and Table 3. The data show that the peak temperature at the central channel is reduced from 232°C to 166°C by going from SiC to the diamond substrate with a TBR of 27 m^{2}K/GW and the diamond thermal conductivity gradient. By considering a uniform conductivity of 1500 W/mK reduces the peak temperature by an additional 7K. A reduction in the TBR to a theoretically low value of 3 mm^{2}K/GW while still considering the gradient in thermal conductivity results in a peak temperature of 152°C. Finally, assuming the low TBR value and no gradient in thermal conductivity results in a peak temperature of 146°C, representing a 20°C drop versus the worst diamond case. Overall, the reduction in peak temperature at 7 W/mm is 30% for this device architecture using CVD diamond assuming the properties that were measured in this study. By reducing the TBR and maximizing the thermal conductivity in the near interface region, a maximum decrease in peak temperature is expected to be closer to 40%.

TABLE III
SUMMARY OF PEAK DEVICE TEMPERTURE

Device	Peak Temperature (°C)
SiC	232
Gradient Dia, TBR = 27 mm^{2}K/GW	166
No Gradient, TBR = 3 mm^{2}K/GW	159
Gradient Dia, TBR = 27 mm^{2}K/GW	152
No Gradient Dia, TBR = 3 mm^{2}K/GW	146

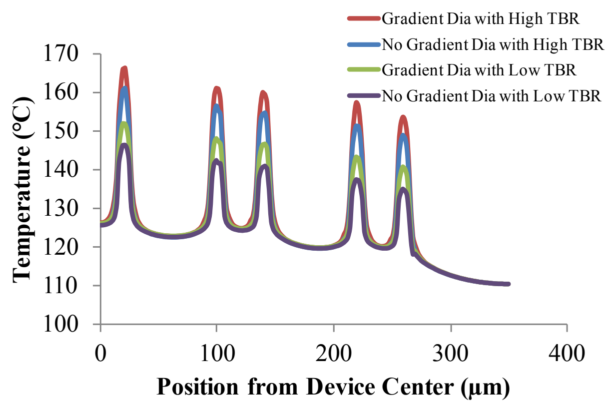

Figure 4. Graph showing the temperature distribution for the channels from the center to the edge of the 10 finger HEMT for all four combinations of TBR and diamond thermal conductivity

V. Conclusions

The data shows that the measurement of CVD diamond films using TDTR can be performed with good accuracy and repeatability between multiple groups. The thermal conductivity is highly dependent on film thickness close to the growth interface, but changes more slowly was the films move towards the bulk region. Based on thermal modeling, the CVD diamond films in this study are expected to reduce the peak temperature in the GaN HEMT by at least 30% when compared to SiC. Greater advantages of CVD diamond can be observed by reducing the gate-to-gate spacing over the current architecture when compared to SiC.

VI. References

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