Simultaneous Evaluation of Heat Capacity and In-plane Thermal Conductivity of Nanocrystalline Diamond Thin Films

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\textbf{ABSTRACT}

As wide bandgap electronic devices have continued to advance in both size reduction and power handling capabilities, heat dissipation has become a significant concern. To mitigate this, chemical vapor deposited (CVD) diamond has been demonstrated as an effective solution for thermal management of these devices by directly growing onto the transistor substrate. A key aspect of power and radio frequency (RF) electronic devices involves transient switching behavior, which highlights the importance of understanding the temperature dependence of a material’s heat capacity and thermal conductivity when modeling and predicting a devices electro-thermal response. Due to the complicated microstructure near the interface between CVD diamond and electronic material, it is difficult to measure both properties simultaneously. In this work, we use time-domain thermoreflectance (TDTR) to simultaneously measure the in-plane thermal conductivity and heat capacity of a 1-µm-thick CVD diamond film via multi-frequency analysis. We obtain temperature dependent thermal properties by using the pump beam to heat the sample according to increasing power. This mitigates the need for a more complicated setup using a thermal stage but has limited upper temperature boundaries based on the sample geometry and thermal properties. The results show that the in-plane thermal conductivity varied slightly with an average of 103 W/m-K over a temperature range of 302–327 K, while the specific heat capacity has a strong temperature dependence over the same range and compares well with heat capacity data of natural diamond in literature.

\textbf{Introduction}

The exceptional properties of diamond have long been investigated in an effort to take full advantage of this unique material. Single crystal diamond has the highest thermal conductivity of any known three-dimensional solid, up to 2500 W/m-K at room temperature [1]. In addition, diamond is a dielectric material making it well-suited to act as an excellent heat spreader in high power electronic devices [2–4]. Because of the difficulty of integrating natural diamond into electronic devices, synthetic diamond grown through CVD and other techniques has been used since the 1980s [5]. The nature of the diamond growth allows for an environment where both nano and micro-crystalline material can be grown, as well as bulk material with very large grains and thermal conductivities approach their natural counterpart [6–8]. Therefore, significant effort has gone into fully characterizing synthetic diamond of all varieties [9, 10].
In terms of power electronic and radio frequency (RF) devices, CVD diamond has been proposed to integrate with GaN-based high-electron-mobility transistors (HEMTs) as both a heat spreading layer and a device substrate [2, 11–14]. The goal is to significantly improve the heat dissipation of the devices and to decrease the operational temperature. It has been shown that limiting device operational temperature can significantly increase the reliability and lifetime of the device [15]. Both power electronic and RF electronics applications require that the transistors operate under a pulsed condition ranging from a few KHz in power electronics to several GHz in RF amplifiers [16]. This highlights the importance of understanding the temperature dependence of both the diamond heat capacity and the thermal conductivity when designing and modeling devices.

Moelle et al. used a differential scanning calorimeter (DSC) to measure the specific heat of a 300-nm-thick nanocrystalline diamond sample and a 300-µm-thick microcrystalline diamond sample as a function of temperature. They found excellent agreement between the single crystal reference sample and the microcrystalline sample, while the nanocrystalline sample did show some deviation in the specific heat when comparing to the single crystalline and the microcrystalline samples [9]. Recent achievements in CVD diamond growth have revealed the importance of seeding density and especially seed distribution uniformity to facilitate the deposition of high quality NCD films. Ultrasonic treatment of a substrate in nanodiamond suspension has become a standard seeding technique that provides for seeding densities over 10^{12} nuclei/cm^2, uniform distribution of diamond seed, as well as to avoiding damage to the substrate. A low methane to hydrogen ratio during diamond CVD deposition is one of the conditions that prevents secondary re-nucleation and ensures that NCD films exhibit a pronounced columnar grain texture resulting only from a competitive growth of original randomly oriented diamond seeds. The growth of CVD diamond onto electronic material, such as GaN, introduces a nanocrystalline structure that is responsible for an increase in thermal resistance [17–19] as compared to its bulk counterpart. Therefore, it is important to characterize the thermal conductivity and heat capacity of these layers near the growth interface.

In this work, we utilized time-domain thermoreflectance (TDTR) to simultaneously measure the temperature dependent in-plane thermal conductivity and the heat capacity of a 1-µm-thick suspended CVD nanocrystalline diamond membrane. The measurements were performed at five power conditions to introduce heating in the diamond membranes. For each power condition, multi-frequency TDTR was used to obtain different TDTR sensitivities of the heat capacity and the in-plane thermal conductivity. The temperature rise due to laser heating in the membrane was then calculated to measure the temperature dependence of both the heat capacity and the in-plane thermal conductivity simultaneously.

**Sample and methods**

A 1-µm-thick suspended diamond membrane grown via CVD was used to allow for simultaneous measurements of both in-plane thermal conductivity and heat capacity. First, a tensile diamond film was grown on a silicon substrate using 0.3% methane to hydrogen ratio at a temperature of 750°C with a growth pressure of 7 Torr and the microwave power was varied from 800 W to 1400 W during growth. Additional growth details can be found in the following reference [20]. Then through standard photolithography, a square region (3000 µm x 3000 µm) of the silicon substrate was isolated and etched away, leaving a 1-µm-thick suspended membrane of CVD diamond. A schematic of the sample structure is shown in Figure 1.

According to the transmission electron microscopy (TEM) measurements, the sample was found to have an average grain size of 135 nm near the growth surface with a maximum and minimum of 267 nm and 63 nm, respectively. Near the nucleation interface, the average grain size was 97 nm with a maximum and minimum of 198 nm and 27 nm, respectively. The root-mean-square (RMS) surface roughness was measured by atomic force microscopy (AFM) to be 19 ± 2 nm [21]. The cross section of
the suspended diamond layer and grain size information are shown in Figure 2. The suspended diamond membrane forces heat to flow laterally, thereby enhancing the TDTR sensitivity to measure the in-plane thermal conductivity.

TDTR was used to measure the thermal properties of the CVD diamond membrane as well as to heat the diamond membrane by the pump beam which enables temperature-dependent measurements of specific heat. TDTR is an optical pump-probe method used to measure thermal properties of both bulk and nanostructures with an ultrafast laser [22–24]. In this work we used a Ti:sapphire laser oscillating at 80 MHz. Polarizing optics split the laser into two beams (pump and probe). The pump beam is further modulated using an electro-optic modulator (EOM). The modulated pump beam heats the sample surface periodically while the probe beam monitors the temperature of the sample surface via the change of reflectivity after passing through a mechanical delay stage. By moving the delay stage, the probe pulse is delayed with picosecond time resolution relative to the pump. The full travel of the delay stage allows for the probe to infer the thermal decay of the pump pulses on the sample surface. The sample is coated with a thin metal transducer which creates a known heat flux on the sample surface and has a large coefficient of thermoreflectance at the probe wavelength which improves the overall signal-to-noise ratio. The probe beam is reflected from the sample surface and directed to a photodiode that is connected to a lock-in amplifier in sync with the EOM. The signal
pumped up by the lock-in amplifier is then used to estimate unknown thermal parameters by fitting to an analytical heat transfer solution [22, 24]. More details about the system used in this work can be found at the following reference [25].

For TDTR measurements, thin films are usually supported by a substrate that allows for effective heat dissipation, thereby keeping the temperature rise within a few degrees during the measurements [26]. However, in our work, the 1-μm-thick thin film is suspended in air which significantly impedes heat conduction in the through-plane direction. A similar sample structure was measured via TDTR previously by Sood et al. to investigate the anisotropy and inhomogeneity of thermal conductivity for multiple suspended CVD diamond films [27]. They found a strong correlation of grain size with thermal conduction by measuring both sides of the membrane and did consider sample heating by applying a correlated heat capacity in their model. They did not fit for heat capacity and kept the pump power constant to avoid substantial heating of the sample. This inhomogeneity and anisotropy in CVD diamond thermal conductivity has been explored more recently for a 11.8 μm diamond membrane by Cheng et al [28]. Here, we intentionally increased our pump power to heat the sample and fit for the heat capacity and in-plane thermal conductivity. Our relative grain size on the top and bottom of the membrane does not change significantly, and measurements are only performed on the top side of the membrane. The surface temperature of a multi-layered structure under periodic laser heating has been reported in the literature [22–24]. We used these models to estimate the steady-state temperature rise in our measurements for a given pump diameter and incident power. For a pump beam with a 20-μm diameter and a power of 10 mW, Figure 3 shows the calculated steady-state temperature rise for both the membrane and the supported film. It is clear to see that the substrate provides an extra path for heat dissipation as compared to the suspended membrane. The membrane geometry allows for significant heating and subsequent temperature-dependent thermal measurements.

In addition to the capability of heating the sample by the pump beam, the modulation frequencies of the pump beam were varied to separate the in-plane thermal conductivity and the heat capacity of the diamond membrane. Multi-frequency TDTR has been used to simultaneously measure thermal conductivity and heat capacity of supported thin films before [24]. Here, by increasing the pump power rather than using an external heating stage, we show an additional ability to evaluate the temperature dependence of thermal properties. For these measurements, we used a 10x objective with pump and probe spot diameters of 20 ± 0.5 μm and 12.4 ± 0.5 μm, respectively. The pump and probe powers were measured before the objective. The transmission through the objective for pump and

![Diagram](image)

**Figure 3.** Schematic diagram of how the laser energy from the TDTR pump diffuses through the material. When the diamond film is supported on Si, a steady-state temperature rise of 0.4 K is estimated. However, since the heat is forced to transfer laterally on the membrane, a large steady-state temperature rise of 10 K is calculated for the same 10 mW power condition.
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Figure 4. Evolution of the probe-averaged surface temperature rise induced by a 0.735 mW absorbed pump power on the surface of the Al transducer at a frequency of 1.2 MHz. (a) Comparison of the “steady-state” temperature rise due to the 80 MHz repetition rate pulsed heating inherent in the TDTR measurement and an estimate of a comparable continuous wave (CW) laser heating scenario. (b) A transient FEM simulation of the estimated probe-averaged surface temperature for the same conditions assuming a Gaussian heat source on the surface of the Al transducer.

Results and discussion

The derivation of spatial and temporal temperature distributions from a modulated heat source on multi-layered structures has been reported in literature [32, 33]. In this work, we define the temperature rise of the sample as a weighted average steady-state temperature rise across the pump and probe beams. We only consider the steady-state temperature rise so the modulation frequency does not affect our calculation. Due to the transient periodic nature of TDTR measurements, there will always be some temperature fluctuation present in the material system. First is the temperature rise induced using the Ti:sapphire oscillator. The degree to which additional heating occurs will be dependent on the system being measured. Figure 4a shows the calculated magnitude of the temperature rise for the multi-layered system examined in this work. It is estimated once the periodic oscillation due to the additional EOM modulation has reached a “steady-state.” There is approximately a 0.25 K temperature rise, as would be measured from a probe-averaged surface, due to the primary oscillators 80 MHz output. Additionally, the EOM modulation results in an added surface temperature fluctuation that is dependent on the superimposed frequency. Figure 4b shows the results of a transient finite element method (FEM) simulation that was performed in COMSOL for the sample structure measured in this work. The simulation was performed using an axisymmetric model with a time dependent gaussian

probe are 0.7 and 0.6, respectively. The reflectivity of the Al transducer at the pump and probe wavelengths (400 nm and 800 nm) are measured to be 0.90 and 0.85 from both the Al-on-diamond sample and an Al-on-Si reference sample. Even with the ~20 nm RMS surface roughness for the diamond sample, we were able to reflect the incident beam onto an external detector with little to no scattering loss, as was evident from the close comparison to the Al-on-Si sample. In addition, the values measured here agree well with what has been previously reported in literature [29, 30]. The TDTR measurements were carried out at five different pump powers while the probe power was kept constant (2.8 mW). The pump power was set to 10.5, 20.3, 30.2, 40.3, and 50.3 mW before the objective. The absorbed pump power by the Al transducer was 0.735, 1.421, 2.114, and 3.521 mW while the absorbed probe power was 0.09 mW. At each power condition, three frequencies were used for the pump modulation: 1.2, 3.6, and 6.3 MHz. The range of frequencies were selected to provide enough sensitivity to the parameters of interest, which will be discussed later. All the measurements were performed on the same sample spot to avoid the inconsistencies brought about by variation of sample structure [31].
heat flux imposed on the surface of the Al transducer. Insulated boundary conditions were applied on the top and bottom of the sample stack with a constant temperature boundary imposed sufficiently far from the heating event where the Si layer would exist. The simulation was only carried out for the 1.2 MHz scenario since higher frequencies would only result in a reduced oscillation amplitude. Here we find that the amplitude of the oscillating probe-averaged temperature rise is ~1 K. If we combine this with the temperature rise due to the 80 MHz oscillator, we can expect an additional 0.75 K temperature increase from the estimated steady-state temperature at any time during the measurement. This discrepancy in temperature has been accounted for in the error bars shown in.

As shown in Figure 5 (left axis), the 20-µm-diameter pump beam (10.5 mW before objective) heats up the >100 µm-diameter area of the diamond membrane, showing the heat spreading effect. The max temperature rise induced by the pump beam (~7 K) is at the center of the beam while the weighted average temperature rise is ~6.5 K. The right axis of Figure 5 shows the normalized intensity distribution of the probe beam, which is narrowly focused on the center and induces an additional temperature rise of ~0.8 K. Therefore, the overall steady-state temperature rise is ~7.3 K. Room temperature was measured to be 296 K to calculate the absolute temperature. It should be noted that the estimated temperature is assumed at the top surface of the Al transducer where the heat flux is imposed. This is a valid assumption considering the relatively high TBC between the Al/diamond and that a calculation of the estimated thermal penetration depth (TPD) for the highest frequency (6.3 MHz) and highest measured heat capacity (611 J/kg-K) it results in a TPD of ~1.4 µm. According to our FEM simulation, we find that the temperature decay through the Al transducer and the 1 µm diamond layer is ~0.2 K. This again is well within the estimated error of the temperature determination when combined with previously mentioned variations from the pulsed transient method.

The sensitivity of each parameter is defined as a fractional change in the measured signal to an individual parameter $p$:

$$S_p = \frac{d(\ln R)}{d(\ln p)} = \frac{dR/R}{dp/p}$$

(1)

**Figure 5.** The temperature rise distribution induced by the pump beam (left axis) and the probe beam intensity distribution (right-axis).
where $R$ is the measured ratio of the in-phase signal to the out-of-phase signal ($-V_{in}/V_{out}$). It is notable that the positive and negative values only indicate how that parameter changes the direction of the curve, and only the absolute value of sensitivity matters [36]. For the sample studied in this work, there were three unknown parameters of interest: the diamond heat capacity, the diamond in-plane thermal conductivity, and the TBC between the Al transducer and the diamond membrane. For the multi-frequency TDTR technique, it is desirable to have large differences in the sensitivity of individual parameters at a certain frequency [24]. As shown in Figure 6, the sensitivity of the diamond specific heat decreases with modulation frequency while that of the in-plane thermal conductivity increases. Therefore, by including both 1.2 MHz and 6.3 MHz in the data fitting, we were able to effectively separate both parameters. The last unknown parameter, the Al/diamond TBC was significant at all frequencies. Additional parameters of interest include the Al transducer thickness which is measured using a well-documented picosecond acoustics method [37, 38], and the through-plane diamond thermal conductivity. The exact parameters used in the sensitivity analysis are listed in Table 1. The Al thermal conductivity was determined by measuring electrical conductivity and applying the Wiedemann-Franz law. The heat capacity of the Al was held constant at 900 J/kg-K for all of the power conditions, however, an uncertainty of ± 45 J/kg-K was applied during the error estimation to account for slight temperature dependent variances in the heat capacity of the Al.

CVD diamond has been well-documented to have an inherent gradient microstructure through the thickness due to the columnar grain growth [28, 39, 40]. The through-plane thermal conductivity value used here was measured on a spot where the diamond is supported by the silicon substrate. The TDTR measurement was taken at 11.6 MHz with a 5x objective to induce near 1D heat transfer through the diamond. We obtained an effective value of 175 ± 65/-42 W/m-K for the through-plane diamond thermal conductivity [20], and is consistent with the reported values in literature [31, 41, 42]. Additionally, we estimate a diamond/Si TBC of 92 ± 21/-27 MW/m²K. The large error results from the reduced sensitivity of the through-plane thermal conductivity and the diamond/Si TBC. The through-plane thermal conductivity value along with its uncertainty was used in the data fitting of the suspended membrane as a known parameter. Because of the geometry of the suspended membrane, in-plane heat conduction dominates during the measurements, so the sensitivity of the through-plane thermal conductivity is very small compared with that of the in-plane thermal conductivity and the heat capacity. Therefore, the error in the through-plane thermal conductivity has a negligible impact on the measurements of the in-plane thermal conductivity and the heat capacity.

![Figure 6. Sensitivity plots for the unknown parameters at three frequencies. Since the sensitivity of the heat capacity and the in-plane thermal conductivity are distinctly different at low and high modulation frequencies, we were able to fit for both parameters.](image)

**Table 1.** Material properties used in the TDTR sensitivity analysis and data fitting. $C_p\text{diamond}$, $k_r\text{diamond}$, and $G\text{diamond}$ are unknown parameters.

| Material | $k_r$ [W/m-K] | $k_i$ [W/m-K] | $\rho$ [kg/m³] | $C_p$ [J/kg-K] | $d$ [nm] | $G$ [MW/m²-K] |
|----------|---------|---------|---------|---------|---------|---------|
| Diamond  | 175 + 65/-42 | fit     | 3500    | fit     | 1000 ± 50 | fit     |
| Al       | 175 ± 35  | 175     | 2700    | 900 ± 45| 87 ± 3a  | fit     |

aAl transducer thickness measured by picosecond acoustics [37]
The fitting of the experimental data with the analytical solution is shown in Figure 7 and excellent agreement is achieved for all the power conditions. The error bars were calculated by a Monte Carlo method in which we assigned an uncertainty to each parameter in the model and those parameters were randomly varied within the uncertainty bounds before fitting for the three unknown parameters. This is repeated 500 times to develop a distribution. The 50th percentile value is taken as the measured value with the 90th and 10th percentile being used as the upper and lower error bounds [25]. The measured diamond heat capacities are shown in Figure 8. We also included literature values of natural diamond as comparison [34, 35].

Both theoretical and experimental methods have demonstrated deviations of diamond heat capacity as a function of grain size [9, 43]. Adiga et al. performed molecular dynamics simulations for a ultra-nanocrystalline diamond system consisting of ~4 nm grains and found an approximate 20% higher heat capacity as compared to single-crystal diamond at room temperature [43]. These variations were attributed to changes in the phonon dispersion because of characteristic length scales reduction and phonon softening at grain boundaries due to enhanced sp² hybridization. Moelle et al. used DSC to evaluate nanocrystalline diamond with a 20 nm average grain size and a hydrogen concentration of 10%. They measure an increase in specific heat of ~25% at 50°C as compared to single-crystal diamond. This increase is primarily assumed to come from the incorporated hydrogen.

![Data fitting of the experimental data (circles) to the analytical model (lines) for three frequencies simultaneously.](image)

![The heat capacity of the nanocrystalline diamond membrane measured by TDTR in this work. As comparison, the measured heat capacity data of natural diamond from literature are also included [34, 35].](image)
and sp² hybridization at the grain boundaries [9]. Theoretically, heat capacity should increase as the characteristic length scale for thermal energy transport in the material is reduced [43]. For the sample evaluated in this work, the average grain size was ~100 nm and there did not appear to be any significant increase in the heat capacity as compared to natural diamond measurements from literature [34, 35]. While, the hydrogen concentration in this sample is unknown, the close comparison to natural diamond (Figure 8) would indicate that the grains are large enough to offset impacts of sp² hybridization and hydrogen incorporation on an increase in heat capacity.

Accurate measurements of both specific heat capacity and thermal conductivity are of importance when utilizing diamond to extract heat from power electronic devices and RF devices. Diamond has one of the highest Debye temperatures of any known material which has been reported to be 1800 K – 2200 K [34, 44]. Its heat capacity has a strong temperature dependence below the Debye temperature and will increase significantly at room temperature and above, as shown in Figure 8. The vertical error bars in Figure 8 are calculated by the previously mentioned Monte Carlo method. The horizontal error bars are the highest and lowest calculated temperatures when varying the properties in the model within the associated parameter uncertainties in Table 1.

For the measured in-plane thermal conductivity, our results are consistent with previous reports on the measured in-plane thermal conductivity of CVD diamond films which showed weak temperature dependence within 298–498 K [39, 42, 45, 46]. Graebner et al. used a modified laser flash method to measure the cross-plane thermal conductivity of thick (234 and 144 µm) CVD diamond with grain sizes of ~35 µm. A separate method consisting of thin-film heaters and very fine thermocouples was used to measure the in-plane thermal conductivity of the samples. The measurements were performed from 25°C to 130°C. No temperature dependence on the in-plane thermal conductivity over this range is observed for either sample [39]. Anaya et al. and Hines et al. both use a modified Raman method to evaluate the in-plane thermal conductivity of suspended nanocrystalline diamond membranes 1 µm thick. By utilizing a central heater and measuring the Raman shift of either Si nanowires or TiO₂ nanoparticles they are able to extract the in-plane thermal conductivity assuming 1D lateral diffusion across the center of the membrane and comparing to an FEM model. Additionally, Hines et al. incorporates resistance temperature detectors across the membrane for further verification. They measure in-plane thermal conductivities that vary slightly between 90 and 105 W/m-K over a temperature range from 35°C to 70°C and demonstrate a lack of temperature dependent in-plane thermal conductivity by comparing the data to an assumed power law temperature dependence [42, 46]. The lack of temperature dependent in-plane thermal conductivity is most likely due to phonon scattering at the grain boundaries or scattering due to defects/impurities being the primary mechanism reducing the thermal conductivity. The measured in-plane thermal conductivity in this work did not show obvious temperature dependence. Table 2 lists the measured values for all the power conditions. The in-plane thermal conductivity showed a slight variation from 92 W/m-K to 115 W/m-K with an average of 103 ± 12 W/m-K [20, 31]. Previous measurements of a 1 µm nanocrystalline diamond sample on Si with a 50 nm average grain size showed an effective thermal conductivity of 25 W/m-K when using a similar TDTR method [47]. Large variations in CVD diamond thermal conductivity as a function of grain size have been reported [42, 48] and depend greatly on the diamond quality. Additionally, there is a slight change in the Al/diamond TBC from each power condition with

| Power Before Objective | Total Incident Power at Sample Surface | ΔT | kₚ | Cₚ | TBC Al-dia |
|------------------------|--------------------------------------|-----|----|----|-----------|
| mW                    | mW                                  | K   | W/m-K | J/kg-K | MW/m²K |
| 10.5                   | 0.83                                | 7.3 | 99  | 536 | 214       |
| 20.3                   | 1.51                                | 13.4 | 92 | 553 | 214       |
| 30.2                   | 2.20                                | 19.6 | 106 | 573 | 219       |
| 40.3                   | 2.91                                | 25.9 | 103 | 598 | 218       |
| 50.3                   | 3.61                                | 32.1 | 115 | 611 | 222       |
a high and low value of 214 ± 7 MW/m²K and 222 ± 6 MW/m²K, respectively. It has been shown by Monachon et al. and others that the Al/diamond TBC can vary significantly depending on the surface chemistry and growth conditions. They have reported this value to be as low as 32 MW/m²K and up to 230 MW/m²K by simply changing the surface treatment prior to the metal depositions [49–51].

Here, it should be noted that this method of temperature dependent heat capacity measurements has limited applications and relies on the ability to design a sample set such that localized heating can be isolated to the material of interest. In this case a membrane geometry was very effective as a means to induce relatively significant heating in the diamond. Additionally, layer thicknesses must be well quantified and relative variances accounted for in the thermal property error estimation. An iterative procedure would be required for an unknown material or TBC. First multi-frequency measurements over increasing pump powers would need to clearly demonstrate a strong temperature dependence, then, assuming the measured data is consistent, the temperature could be estimated and error bars applied based on the relative error of the calculated temperature dependent thermal properties.

**Conclusions**

In this work, we used TDTR to simultaneously measure the in-plane thermal conductivity and the heat capacity of a CVD nanocrystalline diamond thin film. The suspended membrane structure allowed us to induce significant laser heating from the TDTR pump beam. By systematically increasing the pump power in the TDTR experiment, we demonstrated the ability to effectively heat the sample to study temperature dependence of the thermal properties. The results show that the in-plane thermal conductivity varied slightly with an average of 103 W/m-K over a temperature range of 302–327 K, while the heat capacity of the diamond showed a strong temperature dependence. The heat capacity was measured to be 536 J/kg-K at 302 K, 553 J/kg-K at 308 K, 573 J/kg-K at 314 K, 598 J/kg-K at 320 K, and 611 J/kg-K at 327 K. A good understanding of the temperature dependence of both the thermal conductivity and the heat capacity is crucial to provide accurate device modeling when integrating CVD diamond into both power electronic and RF devices.

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**Disclosure statement**

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