Rapid Characterization of GaN-on-diamond Interfacial Thermal Resistance Using Contactless Transient Thermoreflectance

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Abstract

Reducing GaN-on-diamond interfacial thermal resistance is crucial to maximize the thermal benefit of diamond substrates for high power transistor applications. In this work, we demonstrate a rapid, contactless transient thermoreflectance technique to assess the interfacial thermal resistance of as-grown GaN-on-diamond wafers.

INTRODUCTION

The increasing power density in GaN-based HEMTs makes thermal management in such devices critically important. CVD polycrystalline diamond of high thermal conductivity offers superior heat removal capability near the device junction compared to state-of-the-art SiC substrates. The latest GaN-on-diamond HEMTs have demonstrated excellent device characteristics [1] and scalability [2]. This GaN-on-diamond technology starts with a MOCVD-grown AlGaN/GaN epilayer on Si, and involves depositions of a thin dielectric seeding layer and CVD diamond on the exposed GaN surface, following the removal of Si and nitride transition layers [1,2]. The amorphous dielectric interlayer and the nucleation region of initial diamond growth result in an effective thermal boundary resistance (TBR_{eff}) at the GaN/diamond interface, which constitutes a major thermal barrier that limits to gain the full thermal benefit of diamond [3]. This TBR_{eff} is strongly dependent on the growth conditions, and measurement of this parameter as an essential step in optimizing GaN-on-diamond technology is therefore crucial.

Existing TBR_{eff} characterization methods include ultrafast laser-based TDTR and Raman thermography, which require either a metal transducer deposition or device fabrication (and hence long feedback times). The aim of this paper is to demonstrate a transient thermoreflectance method to characterize GaN-on-diamond TBR_{eff} on a wafer level. This fully contactless and non-destructive technique does not require any additional deposition or processing and can therefore be used on as-grown wafers prior to device fabrication. The rapid evaluation of wafer thermal resistance provides fast feedbacks to GaN-on-diamond wafer manufacturers, and enables them to refine growth conditions for improving the device thermal performance.

MEASUREMENT TECHNIQUE

The nanosecond transient thermoreflectance developed here is a laser-based pump-probe technique. A 10 ns, 355 nm pulse laser (3rd harmonic of a Q-switched Nd:YAG laser) above the GaN bandgap is used as a pump beam to impulsively heat the AlGaN/GaN surface. This temperature rise induces a change in the surface reflectance which is

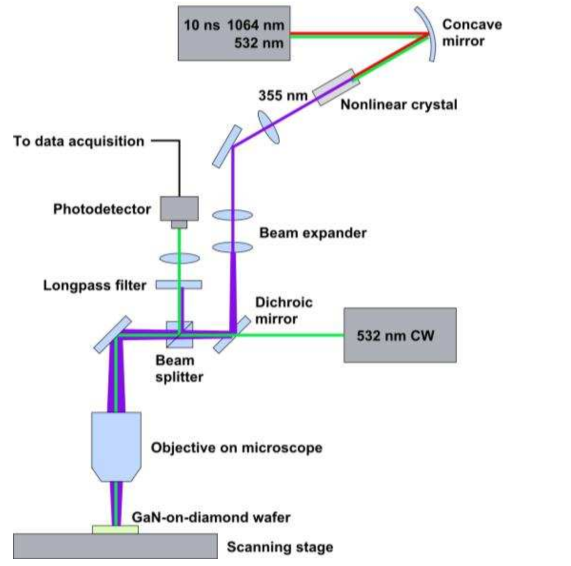

Figure 1. Schematic of the transient thermoreflectance measurement setup.

linearly temperature dependent. A 532 nm CW laser (2nd harmonic of Nd:YAG) is used as a probe beam to monitor this reflectance (and thus temperature) change in the time domain. The two laser beams are aligned coaxially and directed to a standard microscope for convenient wafer mapping. The sample surface temperature rapidly rises upon the pulse UV laser excitation, and subsequently relaxes due to heat diffusion within the GaN layer, across the interface

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and into the diamond substrate. A fast, amplified Si photodetector is used to record the intensity of the probe laser reflected off of the sample surface. A schematic of the experimental setup is shown in Figure 1, with more details of the measurement described in Refs. 4 and 5.

To extract the thermal properties including TBR_{eff} from each measured transient, a 3-D finite element thermal model was employed to calculate the transient temperature at the AlGaN/GaN surface. The only fitting parameters in this model were TBR_{eff} of the GaN/diamond interface and the thermal conductivity of the diamond substrate. A least-square minimization procedure was used to determine the fit values.

The basis of the thermoreflectance technique is that the reflectance change is linearly proportional to the surface temperature rise. For GaN-on-diamond, the dominant reflection occurs at the AlGaN/GaN surface with the greatest refractive index contrast (n_{air} = 1 and n_{GaN} ~ 2.4, $n_{diamond}$ ~ 2.4), making this measurement most sensitive to surface temperature modulations. Nevertheless, challenges arise due to remaining sub-surface reflections that may contribute to the total reflectance. This results in a reflectance spectrum as illustrated in Figure 2. Since the refractive index is a

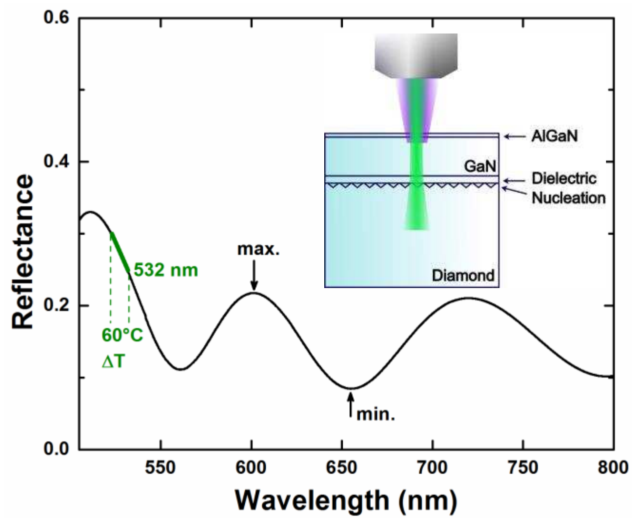

Figure 2. Spectrally resolved reflectance of a GaN-on-diamond wafer as a result of the sub-surface reflections in the layer structure shown in the inset. The 532 nm wavelength is within regions where a linear approximation between reflectance change and surface temperature rise is valid. If the probe laser wavelength is near the local maximums or minimums, large temperature modulations may make the linear assumption no longer valid.

function of both wavelength and temperature, a temperature increase is equivalent to a shift in wavelength for the total reflectance. If such a shift crosses a local maximum or minimum of the reflectance spectrum in Figure 2, the reflectance response may not be linear with the surface temperature modulation. Cautions have been taken to ensure a reasonably good linear relationship between the reflectance change and the surface temperature increase. First, the probe laser wavelength (532 nm) chosen here is not in the vicinity of the maximums or minimums of the reflectance spectrum. Based on the temperature [5] and wavelength [6] dependences of the GaN refractive index, a surface temperature rise of 60 °C corresponds to a 10 nm shift in the wavelength (Figure 2). In our measurements, the peak temperature modulation is less than 60 °C, within regions where a linear approximation is valid. This is further justified by the fact that varying the pump laser power induces no change in the normalized transient. Secondly, identical thermoreflectance decays were obtained on wafers with and without a gold transducer [4], verifying that the signal response indeed originates from the surface temperature change. Finally, we validate our results using a thermo-optic model which takes into account sub-surface reflections, and the calculated reflectance change scales with the surface temperature rise on the timescales of interest (> 100 ns). We also notice that an alternative option to overcome the challenge is to use an above-bandgap probe beam, which monitors only the surface reflectivity, and this can be generalized to characterize other unprocessed GaN wafers including GaN-on-Si and GaN-on-SiC, as well as many other material systems without the need for a metal transducer. The development of this generic technique is in progress.

RESULTS AND DISCUSSION

Figure 3 shows the time-resolved normalized reflectance change of a series of GaN-on-diamond wafers studied here, each having a dielectric interlayer thickness from 28 nm to 100 nm, and a diamond substrate grown by either hot filament (HF) CVD or microwave (MW) plasma CVD. A faster decay in the transient indicates a lower TBR_{eff}, as heat diffuses more efficiently into the diamond substrate. This

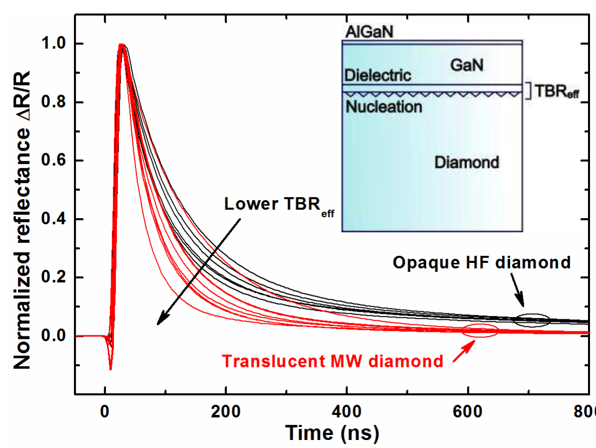

Figure 3. Normalized transient reflectance of GaN-on-diamond wafers with different thicknesses of the dielectric seeding layer. Two diamond growth methods were used: Hot filament (HF) CVD and microwave (MW) plasma CVD. Inset shows a schematic of the sample layer structure.

measurement is most sensitive to TBR_{eff} since the GaN/diamond interface is the predominant thermal barrier. The effect of the diamond substrate, however, also contributes to the transient as seen on the long timescales in

Figure 3. The separation of the two groups of curves beyond 500 ns suggests that the opaque HF diamond has a lower thermal conductivity than the translucent MW diamond. The extracted effective thermal conductivity is 500 – 700 W/m-K for the opaque HF diamond, and 1200 – 1800 W/m-K for the translucent MW diamond. The wide ranges took into account wafer-wafer differences as well as experimental and model fitting uncertainties.

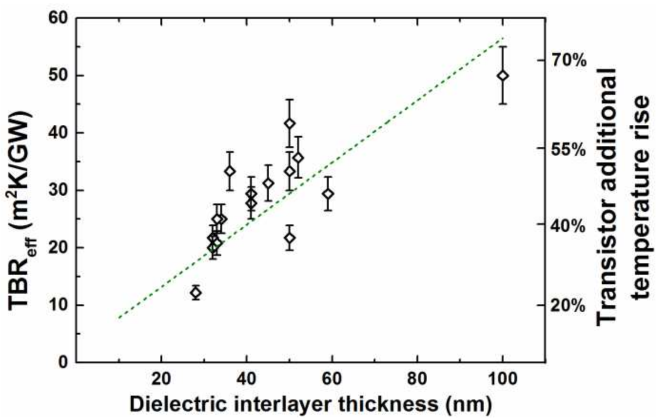

Figure 4. TBR_{eff} of the GaN/diamond interface versus the dielectric interlayer thickness. The corresponding additional transistor-channel temperature rise (in percentage) is indicated on the right vertical axis. The dashed straight line is a guide for the eye.

TBR_{eff} is plotted as a function of the dielectric interlayer thickness in Figure 4, where approximately a linear relationship between the two quantities is evident. This suggests that the interfacial thermal resistance is primarily due to the amorphous dielectric interlayer used for diamond growth seeding. The deviations from an exact linear relationship are likely due to the contribution of the diamond nucleation surface that varies from wafer to wafer, for which a detailed analysis can be found in Ref. 7.

The GaN-on-diamond TBR_{eff} values measured here are comparable to those of GaN-on-SiC [8], while the higher thermal conductivity of diamond in comparison with SiC is anticipated to result in an improved heat spreading capability. To assess the device thermal performance, we use a multi-finger transistor thermal model (see details in Ref. 7) to calculate the channel temperature rise corresponding to each TBR_{eff}. A diamond thermal conductivity of 1500 W/m-K was assumed in the model according to the measured results of the translucent MW diamond. The percentage of additional temperature rise with respect to the case of zero TBR_{eff} is shown on the right vertical axis of Figure 4. This highlights the importance of reducing TBR_{eff} to lower the device thermal resistance. If we decrease TBR_{eff} from 50 m^2K/GW to 10 m^2K/GW, the additional temperature rise due to TBR_{eff} can be reduced from nearly 70% to 20%.

CONCLUSIONS

A contactless transient thermoreflectance technique for measuring GaN-on-diamond TBR_{eff} is demonstrated, which enables rapid thermal characterization on a wafer level. A number of GaN-on-diamond wafers using both HF and MW diamond growth methods were assessed; TBR_{eff} is shown to be largely dependent on the thickness of the dielectric interlayer. The role of TBR_{eff} in device thermal resistance is highlighted by using measured thermal properties in a transistor thermal model.

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REFERENCES

[1] D. C. Dumka, T. M. Chou, F. Faili, D. Francis, and F. Ejeckam, IEEE Electron Lett. **49(20)**, 1298 (2013).

[2] D. Francis, F. Faili, D. Babic, F. Ejeckam, A. Nurmikko, and H. Maris, Diamond Relat. Mater. **19(2-3)**, 229 (2010).

[3] J. W. Pomeroy, M. Bernardoni, D. C. Dumka, D. M. Fanning and M. Kuball, Appl. Phys. Lett. **104(8)**, 083513 (2014).

[4] J. W. Pomeroy, R. B. Simon, H. Sun, D. Francis, F. Faili, D. J. Twitchen, and M. Kuball, IEEE Electron Device Lett. **35(10)**, 1007 (2014).

[5] N. Watanabe, T. Kimoto, and J. Suda, J. Appl. Phys. **104(10)**, 106101 (2008).

[6] N. A. Sanford, L. H. Robins, A. V. Davydov, A. Shapiro, D. V. Tsvetkov, A. V. Dmitriev, S. Keller, U. K. Mishra, and S. P. DenBaars, J. Appl. Phys. **94(5)**, 2980 (2003).

[7] H. Sun, R. B. Simon, J. W. Pomeroy, D. Francis, F. Faili, D. J. Twitchen, and M. Kuball, Appl. Phys. Lett. in press.

[8] A. Manoi, J. W. Pomeroy, N. Killat, and M. Kuball, IEEE Electron Device Lett. **31(12)**, 1395 (2010).

ACRONYMS

TBR_{eff}: Effective Thermal Boundary Resistance
HEMT: High Electron Mobility Transistor
CVD: Chemical Vapor Deposition
MOCVD: Metal-Organic CVD
TDTR: Time-Domain Thermoreflectance
CW: Continuous Wave
HF: Hot Filament
MW: Microwave