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

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INTRODUCTION

The increasing power density in GaN-based HEMTs makes thermal management 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, following the removal of Si and the transition layers [1,2]. The amorphous dielectric interlayer and the initial nucleation layer of diamond growth result in an effective thermal boundary resistance (TBR_{eff}) at the GaN/diamond interface, which is 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 a feedback to wafer manufacturers is therefore crucial. The aim of this work is to demonstrate a transient thermoreflectance method to characterize the GaN-on-diamond TBR_{eff}. This fully contactless technique does not require any additional deposition and can be used on as-grown wafers prior to device fabrication. The rapid evaluation of wafer thermal resistance enables GaN-on-diamond wafer manufacturers to refine the growth conditions for improving the transistor thermal performance.

MEASUREMENT TECHNIQUE

The nanosecond transient thermoreflectance developed here is a laser-based pump-probe technique [4]. A 10 ns, 355 nm pulse laser (3rd harmonic of Nd:YAG) above the GaN band gap 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 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 surface temperature relaxes due to heat diffusion into the GaN layer and diamond substrate, and in this way thermal properties including TBR_{eff} can be extracted from the temperature transient. The two laser beams are coaxially directed to a standard microscope for convenient wafer mapping. An amplified Si photodetector is used to record the intensity of the probe laser reflected from the sample surface. A schematic of the experimental setup is shown in FIG. 1.

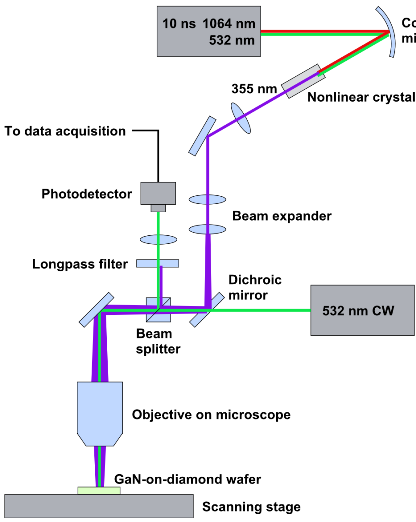

FIG. 1. Schematic of the transient thermoreflectance measurement setup.

Under certain conditions, due to partially coherent internal reflections if the probe laser wavelength is in the vicinity of the maximums or minimums of the total reflectance spectrum, the reflectance change may not be proportional to the surface temperature modulation. The probe laser wavelength (532 nm) chosen here does not fall into these "nonlinear" regions, which is illustrated in FIG. 2. Since the refractive index is a function of both wavelength and temperature, a temperature rise of 60 °C is equivalent to a 10 nm shift in wavelength for the reflectance, calculated using the wavelength [5] and temperature [6] dependence of the GaN refractive index. In our measurements, the maximum temperature modulation is less than 60 °C, within regions where a linear approximation between reflectance change and surface temperature rise is valid, and a variation in the pump laser power causes no change in the transient.

Moreover, identical thermoreflectance decays were obtained on wafers with and without a gold transducer [4], verifying that the response indeed originates from the surface temperature.

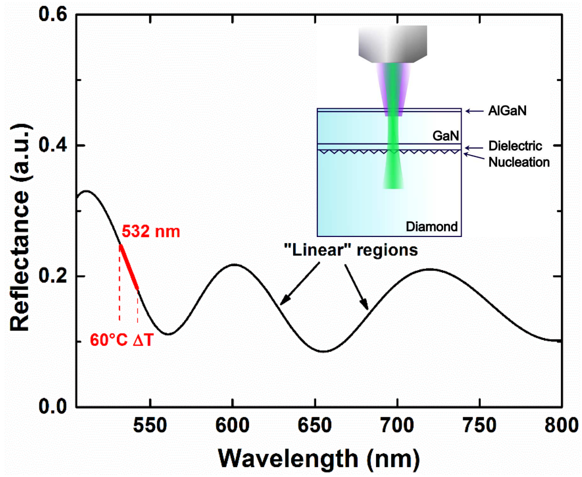

FIG. 2. Measured reflectance spectrum of a GaN-on-diamond wafer as a result of the partially coherent internal reflections of the probe laser, as illustrated in the inset. The 532 nm wavelength is within the regions where a linear approximation between reflectance change and surface temperature rise is valid.

RESULTS AND DISCUSSION

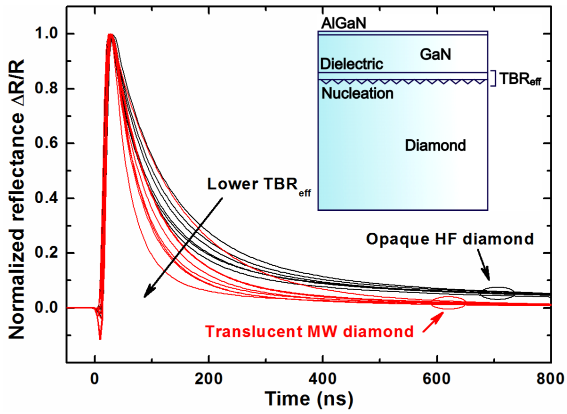

FIG. 3. Normalized transient reflectance of GaN-on-diamond wafers with different thicknesses of the dielectric seeding layer. Two diamond growth methods were used: Hot filament (HF) CVD and microwave (MW) plasma CVD. Inset shows a schematic of the sample layer structure.

FIG. 3 shows the time-resolved normalized reflectance change of a series of GaN-on-diamond wafers studied here, each having a nominal thickness of the dielectric seeding layer 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 (and thus the surface temperature) indicates a lower TBR_{eff}, as heat diffuses more efficiently into the diamond substrate. This measurement is most sensitive to TBR_{eff} since the GaN/diamond interface is the dominant heat barrier. The effect of the diamond substrate, however, also contributes to the temperature transient as seen on the long timescales in FIG. 3. The separation of the transients beyond 500 ns suggests that the opaque HF diamond has a smaller thermal conductivity than the translucent MW diamond.

The measured transients were fit with a finite element thermal model and the extracted TBR_{eff} is plotted as a function of the dielectric interlayer thickness in FIG. 4. TBR_{eff} follows approximately a linear relationship with the dielectric layer thickness; the deviations are likely due to the contribution of the diamond nucleation surface that varies from wafer to wafer. Using a multi-finger transistor thermal model [4], the peak channel temperature rise corresponding to each TBR_{eff} was calculated and shown on the right vertical axis. This highlights the importance of reducing TBR_{eff} to lower the device thermal resistance. By decreasing TBR_{eff} from 50 m^2K/GW to 12 m^2K/GW, the transistor channel temperature rise can be reduced by 30%.

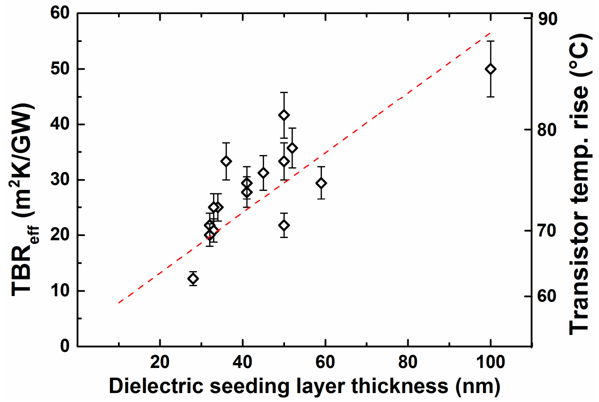

FIG. 4. TBR_{eff} of the GaN/diamond interface as a function of the dielectric seeding layer thickness. The corresponding transistor peak channel temperature rise is indicated on the right vertical axis. A straight line is shown for visual guidance.

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ACRONYMS

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