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Thermal characterization of GaN heteroepitaxies using ultraviolet transient thermoreflectance*

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Thermal transport properties of GaN heteroepitaxial structures are of critical importance for the thermal management of high-power GaN electronic and optoelectronic devices. Ultraviolet (UV) lasers are employed to directly heat and sense the GaN epilayers in the transient thermoreflectance (TTR) measurement, obtaining important thermal transport properties in different GaN heterostructures, which include a diamond thin film heat spreader grown on GaN. The UV TTR technique enables rapid and non-contact thermal characterization for GaN wafers.

Keywords: GaN heteroepitaxy, thermal conductivity, transient thermoreflectance, ultraviolet laser

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1. Introduction

As the power density in GaN-based transistors has increased, thermal management has become a key issue that affects device performance and reliability.[1] Heat dissipation starts from near the GaN heterojunction, thus the heat spreading capability of the device is intrinsically determined by the thermal properties of the layers constituting the heterostructure. In particular, the interfacial thermal conductance is related to the substrate-dependent interfacial layer and material boundaries. To improve heat dissipation from the GaN epilayer to the substrate, it is therefore important to characterize the interfacial thermal conductance to optimize the growth process.

Laser-based transient thermoreflectance (TTR) is an effective technique to measure the thermal conductivity of ∼ 100 nm to 1-μm-thick thin films.[2] TTR does not require device fabrication or patterned heater deposition as needed in Raman thermometry[3] or 3ω method,[4,5] and it is fast in data acquisition and relatively cost-effective compared to time-domain thermoreflectance (TDTR) based on femtosecond lasers.[6] TTR commonly uses visible lasers for heating and probing, and thus for generic measurement purposes, the sample is usually coated with a thin metal film for laser absorption and reflection.[2,7,8] This introduces additional variables in parameter fitting, including the metal thickness and thermal diffusivity, and the thermal boundary conductance at the metal-sample interface. Consequently, it is preferable that the semiconductor surface is directly heated and detected by the lasers. In this work, we employ a tailored transient thermoreflectance technique based on ultraviolet (UV) lasers for direct thermal characterization of a series of different GaN heterostructures.

Transient thermoreflectance is based on the linear relation between temperature and reflectivity,[9] which requires that both the heating and reflection occur only on the sample surface. The measured semiconductor needs to be direct-gap and the laser energy needs to be greater than the bandgap such that the penetration depth is sufficiently small compared to the thickness. Prior work demonstrated junction temperature measurement of GaN high-electron-mobility transistors (HEMTs), and surface stress characterization of GaN wafers using Raman spectroscopy with a 266-nm laser[10] or a 364-nm laser,[11,12] surface temperature mapping of GaN HEMTs using UV light-emitting diode (LED) thermoreflectance,[13] as well as contactless TTR characterization of GaN-on-substrate structures.[14,15] These studies have validated the use of ultraviolet light sources for thermoreflectance measurement.

2. Experimental

We first use two representative epi-wafers (GaN-on-SiC and GaN-on-Si) to validate the UV TTR technique, using which we then characterize a novel diamond-on-GaN struc-

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ture. The GaN-on-SiC wafer consisted of a 350-μm-thick SiC substrate, a 50-nm-thick AlN nucleation layer, and a 1.6-μm-thick GaN epitaxy. The GaN-on-Si wafer consisted of a 350-μm-thick Si substrate, a 3.5-μm-thick nucleation/transition layer, and a 1.6-μm-thick GaN epitaxy. The diamond-on-GaN wafer originated from a commercial (002) oriented 300-μm-thick GaN single crystal with double sides polished. A 10-nm-thick SiN_x interlayer was then deposited by magnetron sputtering and the substrate was subsequently seeded by spin coating with nanocrystalline diamond water suspension. A 1-μm-thick polycrystalline diamond thin film was finally grown on the structure using microwave plasma chemical vapor deposition (CVD) and the growth detail can be found in Ref. [16]. The structure of the diamond film was analyzed by scanning electron microscope (SEM) and small angle x-ray diffraction (SAXD).

A 355-nm nanosecond pulsed laser was used as the heating source, with the 325-nm photoluminescence (PL) excitation laser as the probing beam for the TTR measurement, both of which have photon energies greater than the bandgap of the GaN ($\sim$ 3.4 eV) at room temperature. The power of the 355-nm pulse laser was 1 mW–3 mW on the surface of the GaN wafers, which corresponds to a surface temperature rise of tens of degrees according to the thermal simulation. This ensures detectable thermoreflectance signals while keeping the temperature only moderately elevated, as the thermal properties are generally temperature dependent. According to the reported absorption spectrum of GaN,[17] the 355-nm and 325-nm lasers have penetration depths of $\sim$ 120 nm and $\sim$ 85 nm in the GaN layer, respectively. This ensures that the heating and detection both occur near the GaN surface, which suits the transient thermal model used for extracting the thermal transport properties.

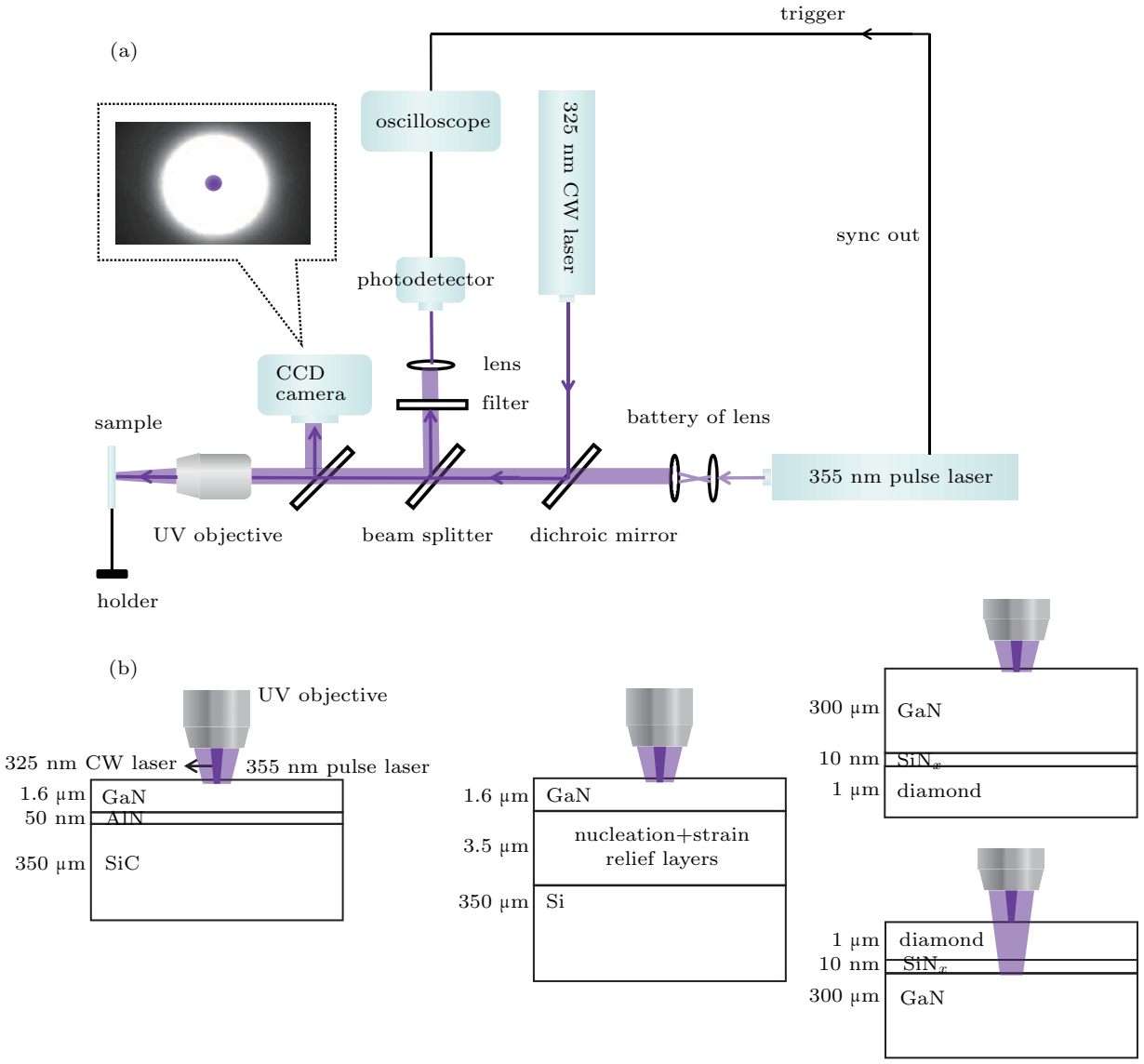


Fig. 1. (a) Schematic diagram of the UV TTR experimental setup. (b) The GaN heterostructures tested in the measurement, and the heating and probing schemes used in TTR for GaN-on-SiC, GaN-on-Si, and diamond-on-GaN.

Figure 1 shows the schematic diagram of the experimental setup and the laser beam alignment on the GaN wafer. The 325-nm continuous wave (CW) probe laser was focused on the surface of the sample with a spot size of ~ 2-μm through a UV objective. The 355-nm nanosecond laser was expanded with a diverging angle to move the focal plane down below the sample surface such that the heating spot is concentric with the probe laser, with a surface heating diameter ~ 90 μm, much greater than the thickness of the GaN epilayer and the size of the probe laser beam. This ensures that the transient thermal diffusion is close to a one-dimensional thermal transport normal to the film plane, which reduces the measurement uncertainty caused by slight misalignment of the two laser beams. The reflected signal of the 325-nm probe laser from the GaN surface was received by a UV sensitive photodetector. The reflected 355-nm component, together with any possible band-edge PL signal was blocked by a 325-nm bandpass filter. In the case of the diamond-on-GaN wafer, UV TTR was performed on both sides of the wafer. On the diamond side, the heating occurred at the diamond-GaN interface as the 355-nm laser penetrates through the diamond film, whereas the reflectance probing mainly occurred at the diamond surface (explained in detail later). The thermoreflectance transient was recorded on an oscilloscope triggered by the synchronized electronic signal from the 355-nm pump laser, *i.e.*, pulses with a 5-kHz (tunable) repetition rate. During the experiment, we used a charge-coupled device (CCD) camera to monitor the concentric condition of the two laser beams and to evaluate the diameters of the laser spots on the sample, as shown in Fig. 1(a).

3. Results and discussion

The room-temperature photoluminescence spectra in Fig. 2 show that the band edge energy is 363.3 nm, 363.6 nm, and 363.3 nm for the GaN-on-SiC, GaN-on-Si, and diamond-on-GaN (from the GaN side), respectively. This has validated the use of the 355-nm and 325-nm lasers for above-bandgap heating and detection. The three GaN wafers exhibit bumps near 370 nm at room temperature, which can be loosely attributed to bound excitons according to Ref. [18].

The normalized relative changes of reflectance from the GaN-on-SiC and GaN-on-Si wafers are shown in Figs. 3(a) and 3(b), representing the transient change of temperature on the measured surface. A three-dimensional (3D) finite element (FE) transient thermal model is used to extract the thermal properties of the GaN heterostructures characterized in the UV thermoreflectance measurement. The FE model is validated against results using an analytical thermal transport model,[19] yielding identical results in both cases. The input of the FE model includes the thickness and specific heat of each constituting layer,[20] the thermal conductivity of the GaN layer and the substrate,[20] as well as the measured pulse width (~ 12 ns) and diameter (~ 90 μm) of the heating laser on the wafer surface. Consequently, the only fitting parameter in the model is the thermal conductivity of the interfacial layer or the surface coating layer, being the AlN nucleation layer in the GaN-on-SiC wafer, the nitride superlattice strain relief layer in the GaN-on-Si wafer, or the nanocrystalline diamond film in the diamond-on-GaN wafer. Using these input parameters, the simulated temperature on the probed surface is compared with the measured transient to extract the fitting thermal property in each heterostructure.

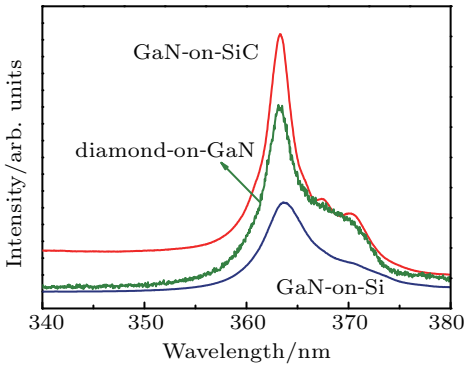


Fig. 2. Room-temperature photoluminescence spectra of GaN-on-SiC and GaN-on-Si, and diamond-on-GaN (from the GaN side).

For GaN-on-SiC, the interfacial thermal conductance between GaN and SiC, $\sigma_{\mathrm{GaN-SiC}}$, is the only fitting parameter in the model, and is extracted to be $(4 \pm 1) \times 10^7$ W/m^2·K. This translates to an interfacial thermal resistance of ~ 25 m^2·K/GW that includes the lumped thermal resistance of the 50-nm-thick AlN nucleation layer and the thermal boundary resistances of the GaN/AlN and AlN/SiC interfaces. The measurement has been validated in two ways. First, the thermal transient measured on the as-grown GaN-on-SiC wafer is compared alongside that measured on the same GaN wafer coated with a thin gold transducer film (~ 200 nm). As shown in Fig. 3(a), the initial deviation before 100 ns between the two transients is associated with the complex electronic and thermal responses of the gold layer following the heating pulse. After 100 ns, the two transients overlap with each other as the gold layer reaches thermal equilibrium with the GaN surface. This verifies that surface heating and probing are achieved using the UV transient thermoreflectance. A similar approach for verification can be found in Ref. [21]. Second, the measured interfacial thermal conductance is consistent with the thermal conductivity value of the 50-nm AlN interlayer characterized by a commercial nanosecond transient thermoreflectance system based on visible/infrared lasers. Moreover, the interfacial thermal resistance of 25 m^2·K/GW falls within the reported range of previously-studied GaN-on-SiC wafers.[22] These facts have delivered adequate confidence for the validity of the present UV TTR measurement.

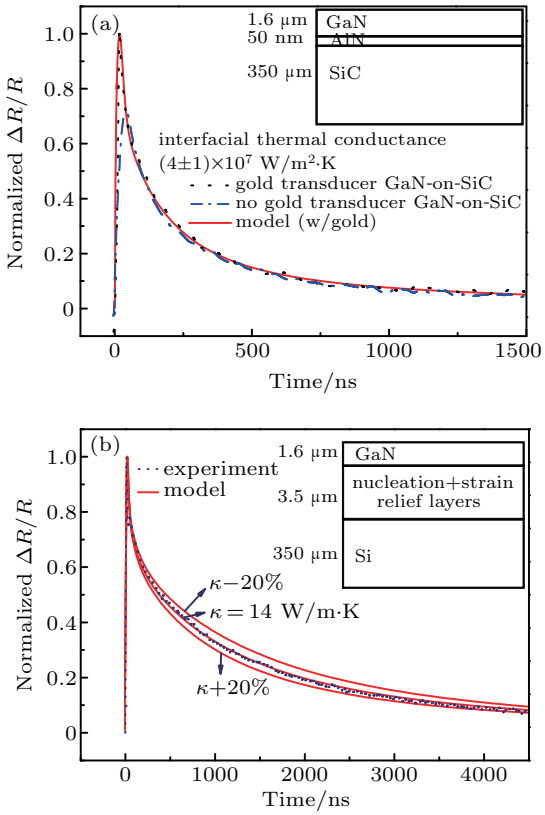


Fig. 3. UV thermoreflectance transients of representative GaN heteroepitaxial structures: (a) GaN-on-SiC (with or without the gold transducer); (b) GaN-on-Si.

For the GaN-on-Si wafer, the interlayer has a 3.5-μm overall thickness that consists of a thin AlN nucleation layer and an AlGaN/GaN superlattice strain-relief layer, which alleviates the lattice mismatch and thermal expansion mismatch. With a thickness even greater than the GaN epilayer, the interlayer cannot be treated as an "interface" in the model anymore. Instead, the effective thermal conductivity of the interlayer is extracted from the fitting to be $\kappa_{\mathrm{GaN-Si,eff}} = 14 \pm 2$ W/mK, as shown in Fig. 3(b), which incorporates the contributions of the AlN layer, the AlGaN/GaN superlattice, as well as the interfaces. The extracted $\kappa_{\mathrm{GaN-Si,eff}}$ is substantially lower than the thermal conductivity of bulk GaN and AlN, and is expected to be close to the thermal conductivity of AlGaN alloys. For comparison, the thermal conductivity of similar alloy films is measured to be $\kappa = 25$ W/mK by 3ω technique.[4,23]

The idea behind the diamond-on-GaN wafer is to use top diamond heat spreaders for enhanced heat dissipation in GaN devices, which has been proposed in recent work.[24] However, it is rather difficult to accurately determine the real thermal conductivity of the polycrystalline diamond thin film as grown on GaN. Figures 4(a) and 4(b) show the SEM images of the polycrystalline diamond film grown on GaN, with a calibrated thickness ~ 1 μm; the SiN_x interlayer is too thin (nominally ~ 10 nm) to be resolved in the SEM imaging. Well-faceted grains are apparent with (111) dominant orientation up to 1 μm in size. The grain size at the top surface on average falls within the range of 0.5 μm–1 μm. The SADX spectrum taken for angles (2θ) between 10° and 130° exhibits (111), (220), and (311) reflexes, as displayed in Fig. 4(c). The diffraction pattern confirms the (111) dominant orientation of the crystallites, in agreement with the SEM observation (Fig. 4(a)).

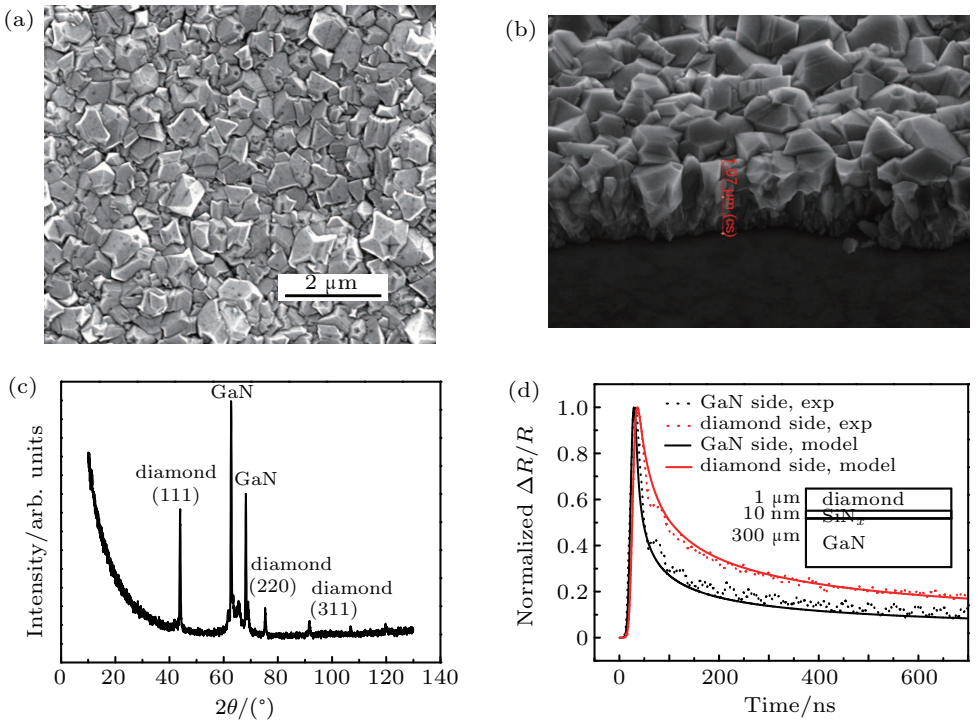


Fig. 4. (a) and (b) SEM images of the polycrystalline diamond grown on GaN. (c) SAXD spectrum taken from the diamond-on-GaN sample. (d) UV thermoreflectance transients taken from the GaN (black) and diamond (red) sides.

For this wafer, the thermoreflectance transient from the GaN side is first recorded, as shown in Fig. 4(d), and in the temporal range, the heat quickly dissipates within the 300-μm-thick GaN layer, making the measurement not sensitive to the thermal properties of any layer underneath GaN. The measurement is also insensitive to the thermal conductivity of GaN in the proper value range for GaN (100 W/m·K–250 W/m·K). We therefore perform a comparison measurement from the diamond side. On the diamond side, the heating occurs at the diamond-GaN interface as the 355-nm laser penetrates through the diamond film, whereas the reflectance probing mainly occurs at the diamond surface due to the similar refractive indices of diamond and GaN. At 325 nm, the refractive index is $2.51+0\mathrm{i}$ for diamond and $2.57+0.35\mathrm{i}$ for GaN,[25] translating to a reflectivity of 0.19 at the air/diamond interface and 0.0048 at the diamond/GaN interface, respectively. An effective thermal conductivity of the nanocrystalline diamond film, $\kappa_{\mathrm{dia,eff}} = 200 \pm 50$ W/m·K, is extracted from the transient fitting (Fig. 4(d)), which includes the contribution of the diamond/SiN_x/GaN interface. This is consistent with reported values for columnar nanocrystalline diamond films grown to this thickness[6] yet on other substrates. The relatively large uncertainty in $\kappa_{\mathrm{dia,eff}}$ is due to the short thermal diffusion time within the thin diamond film which cannot be fully resolved by the heating laser pulse. To improve this, one can use a faster sub-nanosecond or picosecond laser with a faster detector. Nevertheless, the UV TTR technique enables a new approach for nondestructive thermal characterization of diamond thin films as grown on GaN. Note that the signal-to-noise ratio in Figs. 3 and 4(d) varies from wafer to wafer, which could be associated with the difference in the thermoreflectance coefficient or other optical properties between samples.

4. Conclusion

A transient thermoreflectance technique based on ultraviolet lasers is used for thermal characterization of as-grown GaN heteroepitaxies. The measured thermal transport properties include the interfacial thermal conductance ($(4 \pm 1) \times 10^7$ W/m^2·K) of GaN-on-SiC, the effective thermal conductivity of the nucleation/strain relief layers (14 ± 2 W/m·K) in GaN-on-Si, and the effective thermal conductivity of the polycrystalline diamond thin film (200 ± 50 W/m·K) grown on GaN. The UV TTR technique achieves direct heating and probing of the GaN surface and thus can be used as a generic thermal characterization tool for as-grown GaN heterostructures prior to device fabrication.

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