Assessment of channel temperature in β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructure field-effect transistors using visible wavelength thermoreflectance thermal imaging

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ABSTRACT

This work demonstrates direct, rapid 2D thermal mapping measurement capabilities of the ultrawide bandgap semiconductor channel of lateral β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ transistors without sample contamination, long acquisition times, or sophisticated thermometry such as developing novel deep-UV compatible thermoreflectance systems. The temperature rise in the channel of a β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ heterostructure field effect transistor (HFET) was mapped using thermoreflectance imaging at 470 nm. First, the thermoreflectance response of the HFET channel was measured using a monochromator revealing a maximum of the reflectance change around 470-480 nm. Thermoreflectance calibrations were then performed at 470 nm (peak of the reflectance change) and yielded an average thermoreflectance coefficient of $1.06 \pm 0.07 \times 10^{-4}$ K⁻¹. Subsequent measurements of the device (power densities of 0.15-1.47 W/mm, gate-source voltage of 0 V) enabled extraction of a device-level thermal resistance of 51.1 mm·K/W in the channel at the drain-side of the gate. High-resolution, in-situ scanning thermal microscopy measurements of the channel temperature rise show good agreement with and further support the thermoreflectance measurements. Finally, the thermal profile across the entire device length (metal electrodes and semiconductor channel) and width was simultaneously measured using thermoreflectance imaging at 470 nm, and the peak temperature rise was measured in the channel at the drain-side of the gate electrode.

Beta-phase gallium oxide (β -Ga₂O₃) is drawing increased and broader interest from researchers in various fields, as evidenced by the growing number of publications on the topic¹, thanks to its ultrawide bandgap ($E_G \approx 4.8 \text{ eV}$), tunable properties via alloying, and the ability to form β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructures. For example, β -Ga₂O₃ potentially benefits device operation at higher voltages, due to its large (8 MV/cm) predicted critical electric field^{2,3}, and higher temperatures, due to its very low ($\approx 10^{-23}$ cm⁻³) intrinsic carrier concentration.⁴⁻⁶ Additionally, the ability to form alloys with Al, i.e., β -(Al_xGa_{1-x})₂O₃, over a wide composition range (0<x<1) can enable ultra-violet (UV) LEDs with emission tunable from \approx 260 nm (4.8 eV) for β -Ga₂O₃ to \approx 170 nm (7.29 eV) for monoclinic Al₂O₃.⁷⁻⁹ Furthermore, the growth of β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructures in combination with delta-doping yields a two-dimensional electron gas (2DEG) at the β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ heterointerface, analogous to Al_xGa_{1-x}N/GaN high electron mobility transistors (HEMTs).^{9,10} However, the lower thermal conductivity of β -Ga₂O₃ (11-27 Wm⁻¹K⁻¹)^{11,12} with respect to other wide bandgap materials, e.g., GaN $(160-230 \text{ Wm}^{-1}\text{K}^{-1})^{13-15}$ and 4H-SiC $(320-490 \text{ Wm}^{-1}\text{K}^{-1})^{16}$, represents a potential roadblock to the successful deployment of β -Ga₂O₃-based devices.

Accordingly, mapping the peak temperature rise of β -Ga₂O₃-based devices is critical to identify thermal constraints, design thermal management solutions, and optimize device reliability. To assess thermal performance, non-contact optical methods are typically employed, such as infrared thermography, Raman thermometry, and thermoreflectance thermal imaging.^{17–}²⁴ Infrared thermography allows rapid thermal measurements; however, its spatial resolution is poor (3-5 µm) and commonly underestimates the device peak temperature rise in semiconductors that are transparent to the IR radiation.²⁵ Raman thermometry has better spatial resolution (<1 µm), but for β -Ga₂O₃ (4.8 eV, \approx 260 nm), the sub-bandgap excitation wavelengths measure a

through-thickness average temperature rise, and similarly underestimate peak temperature rise.²⁶ Modified Raman methods such as nanoparticle-assisted Raman thermometry and 2D material-assisted Raman thermometry allow temperature measurements of the semiconductor channel surface with better fidelity but require additional sample preparation and contaminate the sample.^{26–28} Thermoreflectance thermal imaging has been widely used to measure the thermal response of microelectronics devices under both steady state and transient operation due to its ability to acquire full-field thermal maps with submicron spatial resolution.²⁹ Thermoreflectance is typically implemented with visible wavelength illumination and occasionally with near-UV wavelengths (365 nm for GaN)³⁰, but β -Ga₂O₃ (or other ultrawide bandgap semiconductors) would require deep-UV LEDs, which are not readily available, and expensive optics.³¹ Coating the sample with MoS₂ flakes³¹ or quantum rods³² (few hundreds of nm thick) has been shown to allow full-field thermoreflectance imaging of the surface of the semiconductor channel, but this requires additional sample preparation and inevitably also contaminates the sample.

In this work, we study the temperature rise in the channel of β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ heterostructure field effect transistors (HFETs) using sub-bandgap visible wavelength thermoreflectance imaging. Visible wavelength thermoreflectance imaging of β -Ga₂O₃-based devices remains unexplored as the sub-bandgap energy of the probing illumination has been previously considered unsuitable. Herein, thermoreflectance imaging of the channel temperature rise of ultrawide bandgap devices with visible excitation was validated using temperaturecalibrated scanning thermal microscopy (SThM), bypassing the need for deep-UV probing wavelengths in this type of device structure. Ozone-assisted molecular beam epitaxy (O₃-MBE) was used to grow the

 β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ epitaxial structure. First, a 125 nm thick unintentionally doped (UID) β -Ga₂O₃ layer was grown. Subsequently, a 21 nm thick β -(Al_{0.21}Ga_{0.79})₂O₃ barrier layer was grown with Si delta-doping 3 nm above the β -(Al_{0.21}Ga_{0.79})₂O₃/ β -Ga₂O₃ interface. To form Ohmic contacts to the heterostructure, Si ion implantation was used.³³ For implant activation, the structure was annealed at 925°C for 10 min in N₂ atmosphere. Following implantation and activation, Ti/Au (20/200 nm) was deposited via e-beam evaporation and lifted off to pattern electrodes. A 20 nm thick Al₂O₃ layer was then deposited via atomic layer deposition for a gate dielectric. Finally, Pt/Au (20/200 nm) was deposited via e-beam evaporation for a gate electrode. The devices had a channel width of 75 µm, channel length of 16 µm, gate length of 3 µm, draingate spacing of 12 µm, and source-gate spacing of 1 µm. Additional details of the device structure have been reported previously.⁹ A cross-sectional schematic of the device structure is shown in Fig. 1(a). Using Hall and transfer length method (TLM) structures, the mobility, sheet carrier concentration, sheet resistance, and specific contact resistivity at room temperature were measured to be 61 cm²V⁻¹s⁻¹, 9.55×10¹² cm⁻², 10.76 kΩ/sq, and 4.6×10⁻⁴ Ωcm², respectively.

Optical spectral reflectance was measured at an 8° (near-normal) angle of incidence with a Perkin Elmer Lambda 1050 spectrophotometer over a 200-2500 nm wavelength range (0.5-6.2 eV). An integrating sphere was used to collect both the specular and diffuse reflectance, and the system was calibrated using a spectralon reference sample along with calibrated broadband mirrors. Reflectance and transmittance spectra (Fig. 1(b)) were collected from an epitaxial stack similar to that shown in Fig. 1(a); however, no devices were fabricated on this sample. For this sample, O₃-MBE was used to grow a 250 nm thick unintentionally doped (UID)

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 β -Ga₂O₃ layer followed by a 21 nm β -(Al_{0.16}Ga_{0.84})₂O₃ with Si delta-doping on an Fe-doped (010) β -Ga₂O₃ substrate.



Figure 1. (a) Cross-sectional schematic of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET. (b) Reflectance and transmittance spectra of a Si delta-doped β -(Al_{0.16}Ga_{0.84})₂O₃/Ga₂O₃ heterostructure.

Thermoreflectance thermal imaging was performed using a standard thermoreflectance thermal imaging system equipped with a monochromator and a multi-wavelength illumination module composed of 12 fiber-coupled LEDs.³⁴ First, the relative change in reflectivity ($\Delta R/R_0$) was measured as a function of wavelength to identify the optimal (i.e. maximum of $\Delta R/R_0$) measurement wavelength (Fig. 2(a)). For these measurements, ΔR is the change in reflectance of a device as it is pulsed-biased between the OFF-state (unheated, R_0) and ON-state (heated). A $100 \times$ objective and a fiber-coupled LED (470 nm probe wavelength) were used for the subsequent measurements. Point-by-point calibration maps were acquired and used to convert the measured change in reflectance to temperature rise maps. All thermal measurements were performed with a base temperature of 20°C. Thermal maps were acquired by averaging over 100 frames. An oscilloscope was used during measurement to monitor power dissipation. More details about the thermoreflectance thermal imaging technique have been reported previously.^{20,23,24}

SThM experiments were carried out to obtain high spatial resolution (\approx 50-100 nm) maps of the transistor temperature and surface topography, concurrently.³⁵ Details on the customized atomic force microscopy (AFM) setup and the SThM thermocouple calibration procedure have been reported previously.^{36,37} Given the device size and symmetry, SThM images (1024×128 pixels) were acquired on half of the active channel area resulting in a pixel resolution of 18.5 nm and 195.3 nm in the horizontal (channel width) and vertical (channel length) directions, respectively. The topography map was used to detect any morphological changes to the surface due to device degradation. A baseline (i.e., background) SThM map was acquired prior to powering the device to ensure a uniform thermocouple voltage (i.e., temperature). This reference voltage was subtracted from subsequent thermal images to quantify the device surface temperature rise at various power densities.

Upon normal incidence of light from air (refractive index, $n \approx 1$) to a semiconductor, there will be a finite amount of reflectance (R) due to the difference in refractive index of the two media ^{38,39}:

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \tag{1}$$

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This can be seen in the reflectance and transmittance spectra for a β -(Al_{0.16}Ga_{0.84})₂O₃/Ga₂O₃ heterostructure as shown in Fig. 1(b). At visible wavelengths of interest for thermoreflectance imaging (400-800 nm), approximately 15-20% of the light incident upon the sample surface is reflected. For thermoreflectance imaging, modulation of this reflectivity due to temperature changes (Δ T) can be calibrated and applied for device thermography. Assuming a linear relationship, this is realized by the introduction of a thermoreflectance coefficient (C_{TR})⁴⁰:

$$\frac{\Delta R}{R} = \left(\frac{1}{R}\frac{\partial R}{\partial T}\right)\Delta T = C_{TR}\Delta T \tag{2}$$

For thermoreflectance imaging of the temperature rise in semiconductor devices, the metallization structures are typically the features of interest. This is because the measured change in reflectivity of metals with temperature rise is largely dependent on electronic contributions, namely, the plasma frequency (via carrier density and electron effective mass) and Drude damping (via electron relaxation time).^{41–46} However, for non-metals, there can be several contributing factors including thermal effects, free carrier absorption (plasma effect), bandgap shrinkage, band-filling (Burstein-Moss effect), and electroreflectance.^{38,41,47–51}

Unlike other thermoreflectance-based techniques which employ an optical pump-optical probe setup, thermoreflectance thermal imaging uses an electrical pump-optical probe setup, and this applied electric field can cause changes in reflectance. However, electroreflectance contributions to the measured reflectance signal are relevant for wavelengths in a narrow range around optical transitions at critical points in the Brillouin zone ($\approx 4-5 \text{ eV}$).^{38,52,53} Since the visible wavelengths used in thermoreflectance thermal imaging ($\approx 400-800 \text{ nm}$) have energies in the $\approx 1.5-3.5 \text{ eV}$ range, electroreflectance contributions can be assumed to be insignificant. There can also be carrier-induced changes in the reflectance from bandgap shrinkage, band-filling, and free carrier absorption. Bandgap shrinkage and band-filling effects are most prominent near the

bandgap energy of the semiconductor.^{38,49} Therefore, the aforementioned effects should be insignificant since the probing energy is well below the bandgap energy of β -Ga₂O₃ (\approx 4.8 eV) and also the β -(Al_{0.21}Ga_{0.79})₂O₃ barrier and Al₂O₃ gate dielectric. Free carrier absorption should always result in a decrease in the refractive index which would make the change in reflectance negative.^{38,49} In the thermoreflectance spectra of Fig. 2(a), it can be seen that there is a positive peak in the thermoreflectance response of the semiconductor channel region (between the gate and drain electrodes) of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET (Fig. 1(a)) around 470-480 nm. This measured response is opposite of the effect that free carrier absorption would have on the thermoreflectance spectra.

To experimentally confirm that temperature changes were dominating the thermoreflectance response at 470 nm, a TLM structure (Fig. 2(b)-(d)) was calibrated and subsequently measured with the same bias conditions (P = 2 W/mm, $V_{DS}=27.5V$) but different electrical pulse widths of 600 µs, 1 ms, and 100 ms (20% duty cycle). If electric field or carrier-induced changes dominate the thermoreflectance signal, there should be a negligible effect on the measured temperature rise when increasing the electrical pulse width while operating with the same bias conditions. However, as shown in Fig. 2(e), as the width of the electrical pulse was increased, the measured temperature rise of the TLM structure increases, this indicates that temperature changes are driving the measured change in reflectance. Since the Au-coated electrodes also show a local maximum in thermoreflectance response at 470 nm,^{21.24} the temperature rise of the electrodes were simultaneously measured. This provides even greater confidence in our previous assessment because we also observe that the temperature rise of the

ohmic contact metals of the structure increases in agreement with that of the TLM channel as discussed later.



Figure 2. (a) Thermoreflectance spectrum showing relative change in reflectivity of an β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET at various power densities (V_{GS}=4V). The inset is a photomicrograph of the HFET showing the region from where the thermoreflectance data was averaged (dashed box). D, G, and S correspond to drain, gate, and source, respectively. (b) Photomicrograph of a β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ TLM structure. The arrow shows the location and direction from which thermal profiles were extracted. (c),(d) Thermal maps (λ =470 nm) of the temperature rise of the (c) ohmic contacts and (d) semiconductor channel. (e) Temperature rise across the length of the TLM structure at the same bias condition (P=200 mW, V_{DS}=27.5V) with different electrical pulse widths.

The final consideration for the thermoreflectance measurements is thin film interference. Since the probe wavelength is sub-bandgap, thin film interference can also affect thermoreflectance spectra by introducing interference fringes. When there is no thin film interference, the magnitude of the change in reflectance is linearly proportional to the change in temperature. However, thin film interference leads to non-linear effects whereby changes in temperature also spectrally shifts the reflectance spectra.^{24,54} For the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFETs measured in this study, the 125 nm UID β -Ga₂O₃ film is homoepitaxially grown on a β -Ga₂O₃ substrate, and the 20 nm ALD Al₂O₃ and 20 nm β -(Al_{0.21}Ga_{0.79})₂O₃ barrier are too thin to cause this interference. Accordingly, thin film interference effects should not be observable in the thermoreflectance spectra. To confirm this, the thermoreflectance spectra was measured at different device power densities (i.e., different temperature changes), and as shown in Fig. 2(a), the magnitude of $\Delta R/R_0$ changed without any spectral shifting.

As shown previously in Fig. 2(a), the change in thermoreflectance of the semiconductor channel region (between the gate and drain electrodes) of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET was first measured using a monochromator to determine the optimal probing wavelength for successive experiments. From these measurements, it can be seen that there is a peak in the thermoreflectance response of the semiconductor channel region around 470-480 nm. Accordingly, a full-field calibration of the HFET was performed using a 470 nm LED (Fig. 3(a)), and over five rectangular regions of interest the calibration map yielded an average thermoreflectance coefficient (C_{TR}) of $1.06 \pm 0.07 \times 10^{-4}$ K⁻¹ from the exposed semiconductor surface. A 95% confidence interval is provided for the uncertainty in C_{TR}, calculated as ±2 times the standard error of the mean. Subsequently, the HFETs were operated under DC bias at power

densities ranging from 0.15 to 1.47 W/mm with a gate-source voltage (V_{GS}) of 0 V and the temperature rise in the semiconductor channel was measured using λ =470 nm. A region encompassing the drain-side of the gate to 3 µm into the drain-side of the channel (inset of Fig. 3(b)) was used to extract the average temperature rise in the channel at the drain-side of the gate. Plotting the peak temperature rise in the channel as a function of the power density (Fig. 3(b)), a device-level thermal resistance of 51.1 mm·K/W was extracted, which is comparable with previous studies on lateral β-Ga₂O₃-based transistors.⁵⁵ The uncertainty in the temperature rise was determined by multiplying the magnitude of the temperature rise with the standard error of the thermoreflectance coefficient $\delta C_{TR}/C_{TR}$. Figs. 3(c)-(f) show thermal maps of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET operating at a power densities of 0.38 W/mm, 0.74 W/mm, 1.12 W/mm, and 1.47 W/mm, respectively (V_{GS} = 0 V).



Figure 3. (a) A calibration map (λ =470 nm) of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET. D, G, and S correspond to drain, gate, and source, respectively. (b) Peak temperature rise of the HFET as a function of power density (V_{GS}=0V). The dashed line is a linear fit to the data, indicating the thermal resistance (51.1 mm·K/W). The error bars represent the uncertainty due to the thermoreflectance coefficient, C_{TR}, calculated as two times the standard error of the mean C_{TR}. The inset is a photomicrograph of the HFET showing the region from where the thermoreflectance data was averaged (dashed box), corresponding to the drain-side of the gate to 3 µm into the channel. (c)-(f) Thermal maps (λ =470 nm) of the HFET at (c) P=0.38 W/mm, (d) P=0.74 W/mm, (e) P=1.12 W/mm, and (f) P=1.47 W/mm (V_{GS}=0V).

Next, a calibrated SThM tip was used to validate the peak temperature rise measured by visible wavelength thermoreflectance. This method allowed a non-destructive measurement of the temperature distribution in the channel of the HFET for direct comparison with that measured by thermoreflectance. SThM thermal maps were obtained from the center of the device width to the edge of the mesa (Fig. 4(a)). To compare the temperature rise measured using the two methods, an average temperature rise was extracted from a region encompassing the drain-side of the gate to 3 μ m into the drain-side of the channel (Fig. 4(b)). While the region used for averaging temperature rise from thermoreflectance is larger (longer along the device width), the SThM region begins at the centerline, and the symmetry of the temperature rise near the center of the device width allows for a fair comparison. Fig. 4(c) compares the peak temperature rise measured via SThM and thermoreflectance imaging, showing good agreement between the two methods. The temperature rise measured using SThM is slightly lower than that measured using thermoreflectance (< 15%). One possible explanation for this discrepancy is that thermoreflectance is a non-contact optical technique, whereas SThM uses an AFM tip in contact with the device surface which could have a heat sinking effect. Another more probable explanation is that thermoreflectance probes the temperature of the β -Ga₂O₃ channel layer directly above the heat generation in the device. In contrast, SThM probes the temperature rise at the surface of the device channel (i.e., the Al_2O_3 gate dielectric), which is separated from the β -Ga₂O₃ top surface and heat generation by the 21 nm β -(Al_{0.21}Ga_{0.79})₂O₃ barrier layer and the 20 nm Al₂O₃ gate dielectric layer.

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Figure 4. (a) SThM map of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET at P=0.32 W/mm (V_{GS}=0V). (b) A photomicrograph of the HFET showing where the regions from which thermal data was averaged using both thermoreflectance (dotted box) and SThM (dashed box), corresponding to the drain-side of the gate to 3 µm into the channel. D, G, and S correspond to the drain, gate, and source, respectively. (c) Peak temperature rise measured in the channel of the HFET using both thermoreflectance thermal imaging (circles) and SThM (squares). The error bars represent two times the standard error of the mean temperature which accounts for the propagated uncertainty due to the calibration coefficient uncertainty.

The temperature distribution across the entire length and width of the

 β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET device was further measured with λ =470 nm probing wavelength, which, conveniently, also yields a peak in the thermoreflectance response for the Au-coated electrodes.^{21,24} Fig. 5 shows the temperature distribution across the length (Fig. 5(a) at the centerline of the device width) and width (Fig. 5(b)) of the device at various power densities (V_{GS}=0V). As can be seen in Fig. 5(a), the temperature distribution across the metal electrodes and semiconductor channel is rather continuous and there is good agreement. The temperature rise at the drain-side of the gate was greater than on the gate electrode. This is reasonable since heat generation in the device occurs in the 2DEG below the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ heterointerface. Since the measurement in the channel probes the temperature at the surface of the β -Ga₂O₃ layer but the measurement on the gate probes the temperature at the top of the metal electrode, a finite temperature gradient should be expected. This temperature gradient also increases with power density (and V_{DS}) as heat generation increases and becomes more localized. Fig. 5(b) also shows good agreement between the temperature distribution along the entire width of the device in the channel at the drain-side of the gate and on the gate contact.



Figure 5. (a) Temperature rise across the length of the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET when operating at various power densities (V_{GS}=0V). The temperature distribution was extracted at the centerline of the device width from both the metal electrodes (triangles) and semiconductor channel (squares), as indicated by the inset of the photomicrograph of the HFET. A probing wavelength of 470 nm was used. D, G, and S correspond to the drain, gate, and source, respectively. (b) Temperature rise across the width of the HFET at P=0.38 W/mm (bottom) and P=1.47 W/mm (top) in the channel (circles) and on the gate (triangles) with V_{GS}=0V. The dashed regions in the inset of the photomicrograph of the HFET indicate from where the thermal profile was extracted.

As with any thermoreflectance measurement, there are some non-idealities. For example, near edge features (e.g., drain- and source-side of the gate electrode), there are some outliers in the data which are most likely the result of vibration (i.e., acoustic, stage, microscope head, etc.) during measurement and edge effects.^{56,57} For this reason, it was also not possible to acquire any meaningful thermal data from the narrow, exposed channel region between the gate and source electrodes. Additionally, there was considerable macroscopic surface roughness on the first $\approx 15 \,\mu\text{m}$ of the drain and source electrodes close to the channel, which led to noisy data in that location.^{58,59} However, the surfaces of the drain and source electrodes further away from the channel, were smoother, and accordingly these regions show significantly reduced noise. Despite these inherent measurement difficulties, the overall thermal profile across the β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET is consistent and demonstrates simultaneous measurement of the metal electrodes and semiconductor channel.

The temperature rise in the channel of a β -(Al_{0.21}Ga_{0.79})₂O₃/Ga₂O₃ HFET was measured using visible wavelength thermoreflectance thermal imaging, a feat previously thought unsuitable since the probing wavelength (470 nm) is sub-bandgap for ultrawide bandgap semiconductors. This unconventional approach was validated using temperature-calibrated scanning thermal microscopy, with good agreement between the temperature rise measured by the two methods. Visible wavelength thermoreflectance imaging of the average temperature rise at the drain-side of the gate as a function of power density yielded a device-level thermal resistance of 51.1 mm·K/W for the HFET. Finally, the temperature distribution across the entire length and width of the HFET, including the metal electrodes and semiconductor channel, was simultaneously measured with the same probing wavelength (470 nm). The origin of the peak

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around 470-490 nm in the thermoreflectance response has not yet been fully resolved; however, the authors hypothesize of an impurity-related change in the optical properties of the β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructure.^{60–63} Elucidating the nature of this peak and its existence in a broader set of β -Ga₂O₃ structures, such as bare β -Ga₂O₃ substrates, β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructures with different Al content, and doped β -Ga₂O₃ films, is the subject of future theoretical and experimental work.

This work is significant because it forgoes the need for deep-UV LEDs and special optics to probe the thermal response of ultrawide bandgap β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ HFETs as well as bypasses the need for depositing any extraneous nanoparticles or miscellaneous coatings which otherwise contaminate the device integrity. Furthermore, a single excitation wavelength (470 nm) can be used to measure the temperature rise on the metal electrodes and in the semiconductor channel simultaneously, reducing both the calibration demands and measurement acquisition time.

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DATA AVAILABILITY – The data that supports the findings of this study are available within the article.

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