Monitoring the Transient Thermal Response of AlGaN/GaN HEMTs using Transient Thermoreflectance Imaging

Georges Pavlidis and Samuel Graham

Georgia Institute of Technology, Woodruff School of Mechanical Engineering, Atlanta, GA, 30332, USA
e-mail: sgraham@gatech.edu, Phone: +1 404-894-2264

Keywords: Thermal Characterization, Transient Thermoreflectance, GaN, HEMT

Abstract

Transient thermoreflectance imaging (TTI) is a thermometry technique employed to measure the transient surface temperature rise of GaN HEMTs under pulsed biasing conditions. One challenge faced when attempting to estimate the temperature rise is determining the correct thermoreflectance coefficient. Experimentally, the coefficient can be extracted by assuming a linear relationship between temperature and reflectivity. In this work, an electrical characterization method based on the gate metal resistance is first used to verify the accuracy of extracting the correct coefficient. The close agreement between the TTI performed and the gate resistance demonstrate the viability of this technique to be used to thermally characterize GaN HEMTs under pulsed conditions.

INTRODUCTION

The use of Gallium Nitride (GaN) in high electron mobility transistors (HEMTs) has shown to have great potential for RF devices and power electronics. Due to GaN's inherently high breakdown field strength, typical operating voltages and power densities per unit gate periphery are much higher than that of prior technologies such as GaAs. This implies both higher junction temperatures and fast heating rates for transient high-power conditions. During high drain bias operation, extreme localized joule heating near the gate can cause a mixture of both temporary thermally induced device performance droop and permanent degradation. To obtain the full potential out of these devices, understanding and controlling the device channel temperature is important to their lifetime and reliability. There currently exist several thermometry techniques to estimate the peak channel temperature in GaN HEMT's. While temporally and spatially accurate measurement methods such as Raman Spectroscopy have been developed to monitor the device thermal response under DC biasing conditions [1], the use of transient techniques to monitor the formation of the hotspot under pulsed/RF operation biasing have not been fully investigated.

One technique that has the ability to measure the transient surface temperature rise of both the channel and the gate metal is transient thermoreflectance [2]. The accuracy of this technique is based on how well the thermoreflectance coefficient, T_{ch}, of the surface studied can be determined. Due to thermal expansion effects, using a thermal stage and a thermocouple to determine the thermoreflectance coefficient can introduce error in the measurement of reflectivity. Previous studies have used a combination of electro-thermal modelling and Raman thermometry to adjust the thermoreflectance coefficient of the metal to match the expected results [3]-[5]. While this methodology for validating transient thermoreflectance is accurate, the procedure requires additional complex equipment and long acquisition times. With recent advancements in the development transient thermoreflectance imaging (TTI) technology, a piezoelectric stage can be used to account for thermal expansion during the extraction the thermoreflectance coefficient [6]. In this work, TTI is used to extract the thermoreflectance coefficient of the AlGaN/GaN HEMT passivation layer which is then used to investigate the device's transient thermal response under pulsed bias conditions. The temperature profiles are validated via gate resistance thermometry (GRT) [7], a technique which has shown to have the potential to also monitor the transient thermal behavior of the gate metal under pulsed conditions [8][9].

EXPERIMENTAL DETAILS

In this study, TTI is used to perform full surface temperature mappings of AlGaN/GaN HEMTs on SiC substrate. The devices tested were six fingered devices with a 370 µm gate width and were identical to the devices measured via gate resistance thermometry in [7]. A Microsanj NT220B was used to perform these measurements [6]. One key component to estimate the surface temperature rise, ΔT, via TTI is applying the correct thermoreflectance coefficient, T_{ch}, to the thermally induced optical reflectivity variation detected, ΔR:

$$\Delta T = T_{ch} \cdot \frac{\Delta R}{R}$$

The T_{ch} is both material and excitation source wavelength dependent. With the addition of passivation layers, the T_{ch} of

GaN and the gate metal can change significantly leading to significant errors in the estimated temperature rise via TTI. Furthermore, estimating the true temperature of the surface when measuring the reflectivity can also lead to error in the coefficient. A thermocouple was therefore placed directly on the die of the device to accurately measure the temperature rise in contrast to using the temperature of the Peltier stage. A wavelength sweep was performed to determine the optimal wavelength that results in the highest thermoreflectance signal for both the regions above the gate metal and the GaN channel. Performing the calibration at approximately a 100 °C temperature rise, both the regions resulted in a strong T_{ch} of -2.5×10^{-4}°C^{-1} for a 405 nm LED source. Due to the small gate footprint,the calibration measurements were taken at 50x and 100x magnification.

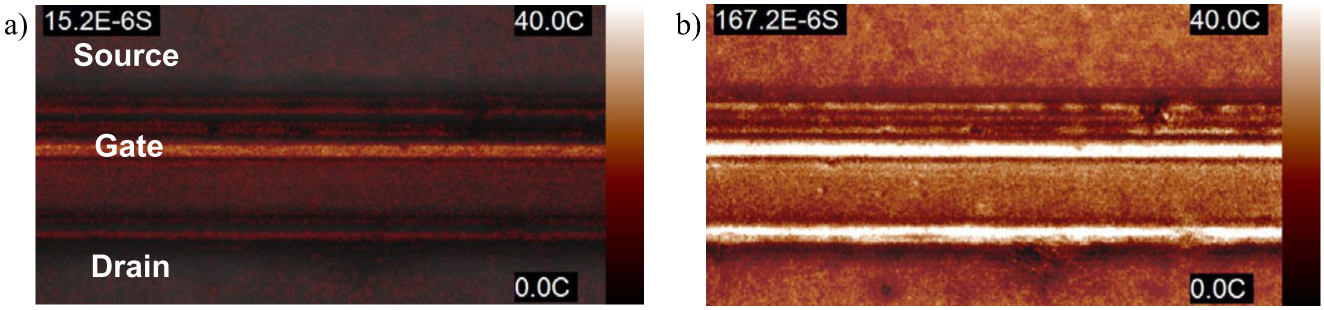

Fig. 1. Transient Thermoreflectance CCD imaging of 6x370 µm GaN HEMT. Drain was biased at 20 V at 40% duty cycle for a 400 µs period. Images were taken at an LED pulse delay of (a) 15.2 µs and (b) 167.2 µs. The area of localized joule heating can be clearly identified by the maximum temperature rise occurring along the gate width.

The devices were biased under pulsed conditions by using an AMCAD Pulsed IV system, similar to the setup described in [7]. A 20 V 400 µs pulse was applied to the drain with varying duty cycle from 10-40% while applying a constant negative gate bias. A 10 µs delay was applied to ensure that the gate bias was applied before the drain bias. The maximum power dissipated was estimated to be 3.9 W/mm. For TTI, an LED pulse width of 6.5 µs was used in order to obtain a strong consistent thermoreflectance signal on the regions of interest. Temperature rises were recorded every 8 µs from 10 to 270 µs. To account for any accumulated heating in the package during pulsed biasing a thermocouple was placed near the package to monitor any temperature rise. The temperature rise estimated via TTI was thus always referenced to the real base temperature. Using an 100x magnification lens, the autofocusing function used for calibrations could also be applied to the TTI imaging reducing the uncertainty in the CCD imaging. While this limits the region of interest to only a quarter of the device, a clear thermoreflectance signal can be obtained from the gate.

To verify the accuracy of this technique, a 4-point transient electrical characterization method using the gate metal resistance was performed simultaneously to TTI. The voltage drop across the gate finger was measured using a Tektronix DPO3012 Oscilloscope and a probe current of 3 mA was applied. Gate resistance measurements were performed every 2 minutes capturing 4 periods each time. An average of all the waveforms captured was taken to directly compare to the TTI temperatures estimated above the gate region. The standard error of the GRT uncertainty was calculated using 95% confidence intervals.

EXPERIMENTAL RESULTS AND DISCUSSION

An example of the temperature rise monitored across the device biased under a 40% duty cycle via TTI is shown in Figure 1. The images shown wereaccumulated over 80 seconds at LED time delays of 15.2 µs and 167.2 µs respectively. Taking into account an applied 10 µs delay, Figure 1a captures the temperature rise at the very beginning of the pulse, the localized joule heating can be uniformly seen around the gate region. Figure 1b represents closely the peak temperature rise in the device throughout the pulse. Based on the results, the peak surface temperature in the device appears continuously over the gate metal region. The heat is shown to spread along the channel where a temperature gradient can be seen along the GaN channel. The drain and source pads appear to have the lowest temperature rise as they are furthest away from the source of localized joule heating. A large temperature rise is shown on the edge side of the drain, this is however is not a true temperature rise as it attributed to edge effects where significant noise is detected by the CCD.

Acquiring images every 8 µs with an 80 second accumulation, the temperature rise and decay of the device under different duty cycles is shown in Figure 2. To directly compare the TTI results to the transient thermal response monitored by GRT, an averaged probed region along half of the gate width was used to accurately represent the same temperature the GRT method is measuring when averaging over the gate metal resistance. Assuming the temperature profile along the gate width is symmetric, the temperature distribution averaged along half the gate width should be identical to the opposite half. The comparison of the GRT transient characterization to TTI in Figure 2 shows good agreement between the two techniques. Using the thermoreflectance coefficient obtained from the calibration the temperature rise of the gate metal aligns almost identically to the GRT measurement under all three duty cycles.

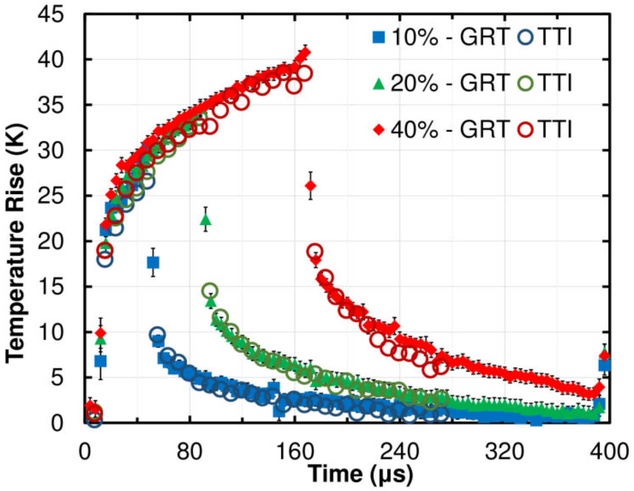

Fig. 2. Transient thermal response of GaN HEMT under various duty cycles for a 400 µs period measured by Gate Resistance Thermometry (solid) and Transient Thermoreflectance Imaging (circles).

Comparing the temperature rises for different duty cycles shown in Figure 2, the results indicate the device does not reach its steady state temperature within 40% of its period confirming the device has a relatively long time constant as suggested in [7]. Furthermore, while the temperature rises for each duty cycle match well with each other, the overall base temperature of the device rises when increasing the duty cycle. This can be observed by the increase in the base resistance measured via the GRT method. Considering the overall average power dissipated increases with longer duty cycles, more heat is accumulated in the package causing an overall increase in the base temperature.

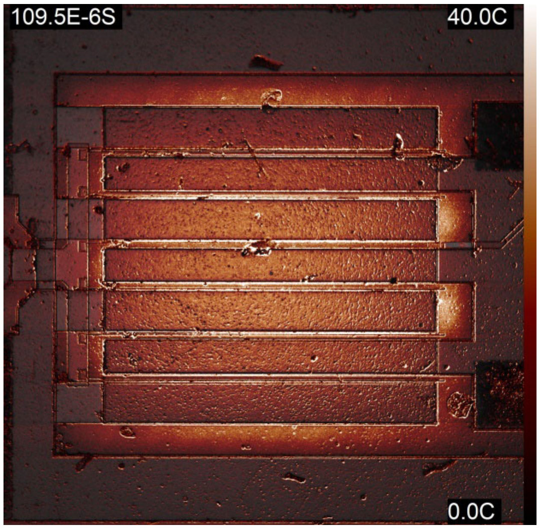

Fig. 3. Transient Thermoreflectance CCD imaging of 6x370 µm GaN HEMT. Drain was biased at 20 V at 25% duty cycle for a 400 µs period. Images were taken at an LED pulse delay of 110 µs.

The close agreement between the TTI and GRT measurements indicate that the thermoreflectance coefficient extracted from the calibration is accurate. The thermoreflectance coefficient can now be used to monitor the temperature rise across the whole device including the GaN, Drain and Source regions. While a T_{ch} of -2.5x10^{-4}°C^{-1} was found along the regions of the Gate, Drain and Source, a T_{ch} of -2.1 x 10^{-4}°C^{-1} was observed in the region above the GaN channel. Using these values, a thermal image of the entire device biased under a duty cycle of 25% is shown in Figure 3. The maximum temperature rise during pulsing is shown to be around 35 °C which agrees well with the transient curve plotted in Figure 2.

To further investigate the device's thermal dynamics, the temperature profiles of the different regions monitored by TTI can also be plotted against each other as shown in Figure 4. Using the appropriate coefficients, the temperature of the gate metal is shown to rapidly rise in temperature and reach a maximum temperature rise of 40 K. While the temperature in the GaN channel is shown to rise to 25 K. Since the hotspot typically occurs right under the gate in the GaN layer, the temperature of the GaN would be expected to be similar to the gate metal as shown in [7]. The discrepancy between the two values measured by TTI can be explained by the source of the thermoreflectance signal. The thermoreflectance signal measured by TTI is mainly attributed to the passivation layer as this is the top surface of the device. The thickness of the passivation layer on top of the gate metal is much thinner than the passivation above the GaN channel. Due to the low thermal conductivity of the passivation layer, a larger temperature gradient will exist between the top surface and the GaN in contrast to the surface temperature measured above the gate metal. The temperatures measured across the drain and source region appear to be the lowest as they are furthest away from the hotspot.

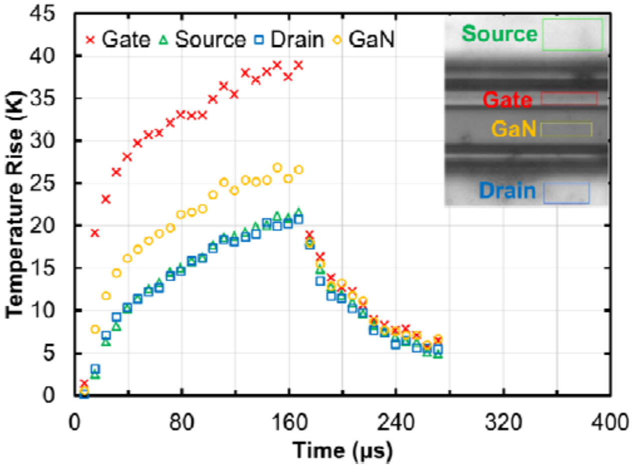

Fig. 4. Temperature profile monitored by TTI of different regions across device for a duty cycle of 40%.

CONCLUSIONS

Overall, TTI shows close agreement with the transient GRT results and the gate metal temperature rise and decay under pulsed biasing is monitored for different drain voltages and duty cycles. The accuracy of extracting the thermoreflectance coefficient using an advanced autofocusing function has been validated when comparing the transient profiles obtained from TTI to GRT. The experimental results show that the peak temperature increases with larger duty cycles and the peak temperature of each cycle corresponds to the end time of each pulse. With the ability to monitor the temperature rise and decay on the microsecond scale, the possibility of extracting thermal time constants to better understand the thermal properties of GaN HEMTs is now possible. While GRT has shown to be a quick reliable method to estimate the junction temperature, TTI has proven to be advantageous for temperature mappings of different regions across the device.

ACKNOWLEDGEMENTS

The authors would like to thank Dustin Kendig (Microsanj) for his extensive technical support and exchange of knowledge of Transient Thermoreflectance imaging.

REFERENCES

[1] S. Choi et al., *Thermometry of AlGaN/GaN HEMTs using multispectral Raman features*, IEEE Transactions on Electron Devices 60.6 (2013): 1898-1904.

[2] K. Maize et al., *Fast transient thermoreflectance CCD imaging of pulsed self heating in AlGaN/GaN power transistors*, In Reliability Physics Symposium (IRPS), 2013 IEEE International, pp. CD-2. IEEE, 2013.

[3] M. Horcajo et al., *Transient thermoreflectance for device temperature assessment in pulsed-operated GaN-based HEMTs*, 2016 CS MANTECH: International Conference on Compound Semiconductor Manufacturing Technology. (pp. 283-286). May 2016

[4] K. Maize et al., *High resolution thermal characterization and simulation of power AlGaN/GaN HEMTs using micro-Raman thermography and 800 picosecond transient thermoreflectance imaging.* Compound Semiconductor Integrated Circuit Symposium (CSICs), 2014 IEEE, pp. 1-8. IEEE, 2014.

[5] L. Baczkowski et al. *Thermal characterization using optical methods of AlGaN/GaN HEMTs on SiC substrate in RF operating conditions.* IEEE Transactions on Electron Devices 62, no. 12 (2015): 3992-3998.

[6] D. Kendig et al. *Thermal analysis of advanced microelectronic devices using thermoreflectance thermography.* Thermal Investigations of ICs and Systems (THERMINIC), 2016 22nd International Workshop on, pp. 115-120. IEEE, 2016.

[7] G. Pavlidis et al., *Characterization of AlGaN/GaN HEMTs Using Gate Resistance Thermometry.* IEEE Transactions on Electron Devices 64, no. 1 (2017): 78-83.

[8] J. Kuzmík et al., *Transient thermal characterization of AlGaN/GaN HEMTs grown on silicon.* IEEE Transactions on Electron Devices 52, no. 8 (2005): 1698-1705.

[9] B. Schwitter et al., *Transient gate resistance thermometry demonstrated on GaAs and GaN FET.* In Microwave Symposium (IMS), 2016 IEEE MTT-S International, pp. 1-4.IEEE, 2016.

ACRONYMS

CCD: Charge-coupled Device
GRT: Gate Resistance Thermometry
HEMT: High Electron Mobility Transistor
LED: Light-Emitting Diode
TTI: Transient Thermoreflectance Imaging