Gate Resistance Thermometry for GaN/Si HEMTs under RF Operation

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Abstract

Gate Resistance Thermometry (GRT) has shown to be a quick and reliable method to estimate the junction temperature of GaN High Electron Mobility Transistors (HEMTs) under DC operation. Real life applications, however, require the devices to be operated under RF where the biasing conditions are not kept constant. Regarding the device's thermal performance, the complex joule heating profile of a HEMT has a high bias dependence and the temperature profile may vary under RF conditions compared to DC operation. An experimental method to evaluate the thermal performance of HEMTs under RF operation is thus necessary. This study shows the first ever GRT measurements performed on GaN/Si HEMTs. A comparative study of gate to gate spacings show that increasing the spacing from 50 to 80 μm decreases the overall temperature rise. A linear correlation is found between the power added efficiency and junction temperature and is attributed to the increase in power dissipated across the device.

INTRODUCTION

The significant growth of AlGaN/GaN high electron mobility transistors (HEMTs) in high frequency electronics has motivated researchers to fully understand the degradation mechanisms in these devices. Operating these HEMTs at higher voltages and power densities, extreme localized joule heating occurs near the gate [1] which can cause thermally induced degradation [2] and directly impact the device reliability. In order to benchmark the device's performance and reliability, accelerated lifetime testing is performed to predict the mean time to failure (MTTF) [3]. This qualification requires an accurate estimation of the gate junction temperature. Despite these devices normally being operated under RF operation, DC accelerated lifetime testing has been primarily used to determine MTTF due to its low operating costs and simpler experimental setup. Consequently, a wide range of thermometry techniques have been developed to estimate the junction temperature under steady state conditions [4]. The joule heating profile across a GaN HEMT, however, is complex and has been shown to have a high dependence on both the drain [5] and gate bias. This signifies that the joule heating distribution will vary during RF operation and will differ to the channel temperature under DC operation [3]. More advanced thermometry techniques are therefore required to estimate the junction temperature under RF operation.

Under DC operation, optical methods such as Raman have shown to accurately measure the temperature across the GaN [6] while also being able to measure the surface temperature of the gate metal using nanoparticle sensors [7]. Electrical methods such as gate resistance thermometry (GRT) can measure the average temperature across the gate metal to give an approximate estimation of the junction temperature [8, 9]. Under pulsed operation, both transient Raman thermography [10] and thermoreflectance imaging [11] have shown to have high temporal resolution down to sub microseconds. Transient gate resistance thermometry (tGRT) has also shown the potential to monitor the transient thermal behavior of the gate metal under pulsed conditions [8, 12].

Due to the complexity of testing under RF operation, the effects of RF signals on the thermal performance of GaN HEMTs has only been once quantified using Raman thermometry [13]. The presence of a field plate, however, restricts the Raman temperature of the GaN to be measured 1 μm away from the gate. GRT can be used to overcome this obstacle by measuring directly the gate metal temperature. In this work, GRT devices designed for RF operation are used to evaluate the thermal performance of GaN/Si HEMTs. For the first time, GRT is used to measure the temperature rise in GaN HEMTs in continuous wave (CW) mode. Key parameters such as the gate to gate spacing and power added efficiency are presented on how they impact RF thermal performance. Transient GRT is also performed to compare transient thermal dynamics of HEMTs.

EXPERIMENTAL RESULTS AND DISCUSSION

The devices tested were AlGaN/GaN HEMTs grown on Si substrate manufactured and processed by MACOM. The device geometry consisted of two 300 μm gate width fingers. The gate-drain spacing and gate-source spacing were 5 μm and 1.1 μm respectively. Two different gate to gate spacings were investigated: 50 and 80 μm. Additional pads were extended from both of ends of a single gate to perform GRT in a four point measurement setup (similar to [14]). A probe current, i_p, was supplied across the gate finger using a Keysight B2902 while a differential probe connected to a Keysight oscilloscope was used to measure the voltage drop across the gate finger.

The differential probe was found to improve the accuracy of the GRT measurement by detecting finer potential differences. Other significant factors contributing to GRT's accuracy included the direction of the probe current in relation to the gate leakage current. To account for any gate leakage, the differential probe was initially calibrated to read approximately 0 V. Subsequently, the probe current was supplied and the potential difference was measured. The main issue encountered with this method is that the gate leakage varied with the operating bias conditions. This resulted in a variable offset resistance as shown in Fig. 1. The differential probe would have to be recalibrated for every single measurement. Without recalibration, the temperature measured by GRT could vary by 5-7 °C.

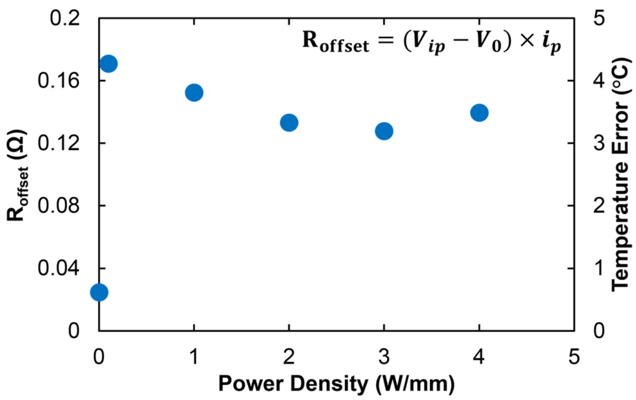

Fig. 1. Effect of power density on the uncertainty of Gate Resistance Thermometry. During operation, significant gate leakage causes an offset in the probe current, i_p, which results in a change in the measured gate resistance that is not due temperature.

To overcome this obstacle, a new peak to peak method was proposed. The voltage across the gate finger was measured under three different conditions: a) no probe current, V_0 b) forward probe current, V_{ip} c) reverse probe current V_{-ip}. The peak to peak resistance was then calculated accordingly:

$$R_{P2P} = \frac{V_{ip} - V_{-ip}}{2} \times i_p \qquad (1)$$

Apart from reducing the error associated with measuring resistance, the effect of the probe current's magnitude and direction on the device's joule heating profile must also be taken into consideration (Fig. 2). Significant current can induce a large potential difference along the gate width causing an asymmetric joule heating profile. The direction of the probe current can thus cause one side of the device to have a more negative gate voltage and result in a reduction of power dissipation. The magnitude of the probe current was thus reduced to 1 mA to prevent any significant voltage drops along the gate width. This required the monitoring of changes in potential difference on the order of microvolts which was possible due to the use of a differential probe.

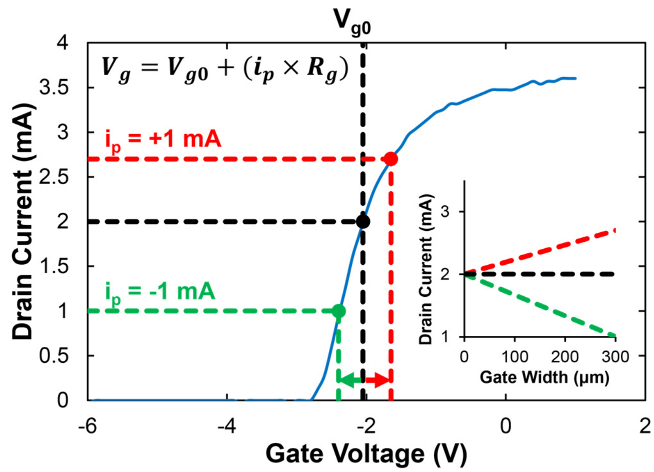

Fig. 2. Effect of probe current's magnitude and direction on Drain current, I_{ds}. Inset shows I_{ds} distribution along gate when probe current is applied.

Wafer measurements were measured on a FOCUS VNA-based load pull stand. The devices were roughly tuned to their peak Power Added Efficiency, P.A.E. A CW small signal Gain of 15 dBm was applied at 2.5 GHz. The devices were operated under Class AB. Devices were biased at 50 V and 20 mA/mm. Power meters were used to record the input (Pin) and the output Power (Pout). Carrier losses were quantified using vector network analyzer.

To assess the effect of the baseplate temperature on junction temperature under RF operation, the baseplate was increased from 25 °C to 125 °C in 25 °C increments. Electrically, the averaged power dissipated across the HEMT was found to increase with base plate temperature and its P.A.E. would consequently decrease. Evaluating the temperature at these conditions, a linear relationship was observed between the temperature rise and P.A.E (Fig. 3).

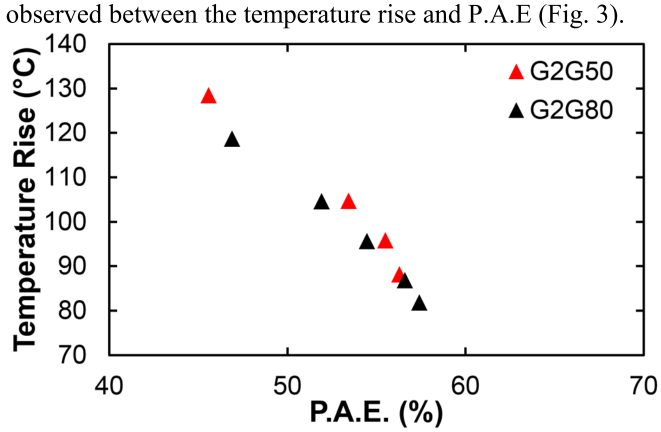

Fig. 3. RF Thermal performance of GaN/Si HEMTs at different power added efficiencies (P.A.E.) evaluated using GRT at different base plate temperatures from 25 to 125 °C.

These results highlight the ability of GRT to evaluate temperature under RF operation and confirms the linear temperature power relationship. Furthermore, the effect of gate to gate spacing on RF thermal performance can be observed where, on average, a 5% decrease in temperature for the 80 µm gate pitch is achieved.

To directly compare the junction temperature measured under DC to RF, the average power dissipated across the device must be known. For RF operation, this power was calculated by subtracting the net gain RF power from the DC dissipated power:

$$P_{DISS} = V_{DS} \times I_{DS} - (P_{RFOUT} - P_{RFIN}) \qquad (1)$$

In doing so, the RF temperature rise measured at a given power density and baseplate temperature can be compared to the temperature measured under a DC bias at the identical conditions (Fig. 4). For both DC and RF operation, the temperature rise increased linearly with power density. Comparing the junction temperature between RF and DC, the temperature rises under RF appeared to be marginally lower than the DC temperature rise. Specifically, for the 50 µm gate to gate spacing, a maximum difference of 4% was observed. This comparison suggests there may exist a difference in temperature profiles across the device channel between RF and DC operating conditions and the effect of bias dependent joule heating. Overall, the change in distribution of joule heating during RF operation result in a lower temperature near the gate metal in comparison to the equivalent DC joule heating distribution.

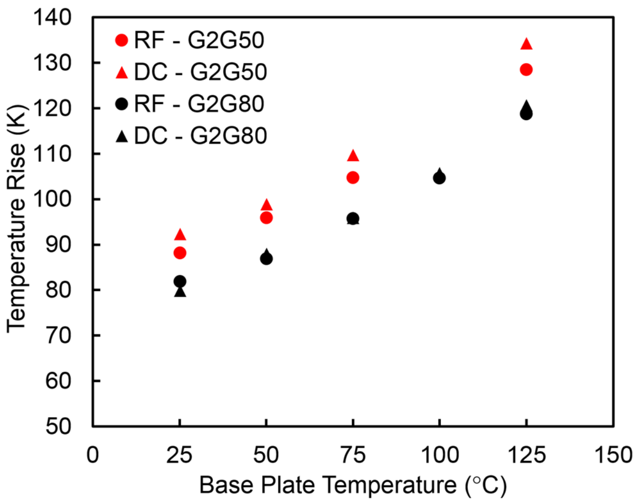

Fig. 4. Comparison of junction temperature measured under RF operation to DC steady state biasing. Temperature were compared for identical base plate temperatures and power dissipated.

To gain deeper insight into the thermal performance of GaN HEMTs under RF operation, transient thermal characterization is thus necessary to monitor the temperature swing in the device. The results of such measurements could then be compared to electrothermal simulations such as those performed in [3]. Limited by the experimental setup for this study, the transient thermal dynamics of the device could only be investigated under pulsed biasing. The devices were biased using an AMCAD Pulsed IV system. A 50 V 360-µs pulse was applied to the drain with a 10% duty cycle. A constant pulsed gate bias was applied to prevent errors in the gate resistance measurements due to change in the leakage currents. A 10 µs delay was applied to ensure that the gate bias was applied before the drain bias. While the experimental setup did not allow for pulsed RF testing, the device's transient thermal profile could be used to assess its performance under high frequency periodic heating. Fig. 5 compares the transient rise and decay for both devices. The 50 µm gate pitch device exhibits a higher temperature rise showing a peak temperature increase of 15%.

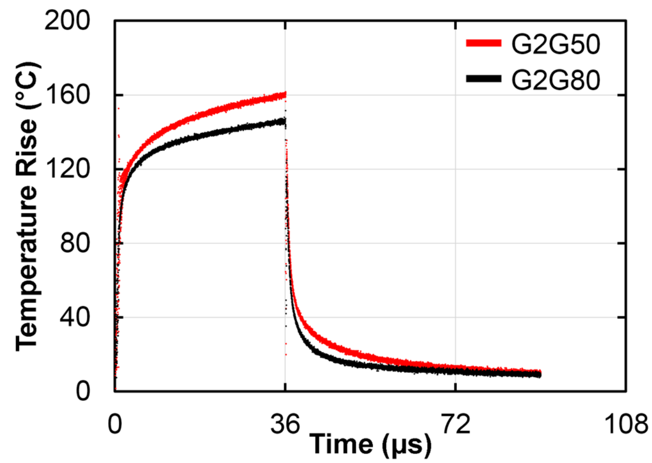

Fig. 5. Transient thermal response of packaged GaN/Si HEMTs with different gate to gate spacings. A 50 V drain bias was applied for a 10% duty cycle.

Conclusions

Overall, GRT has shown to be a quick reliable method to estimate the junction temperature. Using a differential probe, the first ever GRT measurements under RF operation were performed. The technique was used to assess the thermal performance of GaN/Si HEMTs with different gate to gate spacings. The results showed that even under RF, a larger gate to gate spacing improves the device heat spreading and consequently reduces the overall temperature rise. A linear correlation was found between the device's power added efficiency and temperature rise. This can be attributed to the increase in power dissipated across the device. Comparing DC to RF temperature rises, a maximum decrease of 4% was found when operating the device under RF. The reduction in junction temperature under RF confirms the difference in joule heating profiles when the device is biased under DC and RF. To compare these profiles, further electrothermal simulations are required in addition to performing transient GRT measurements under RF operation.

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ACRONYMS/NOMENCLATURE

HEMT: High Electron Mobility Transistor
MTTF: Mean Time to Failure
GRT: Gate Resistance Thermometry
CW: Continuous Wave
P.A.E.: Power Added Efficiency
G2G: Gate to Gate
I_p: Probe Current