Determining Drain Current Characteristics and Channel Temperature Rise in GaN HEMTs

Yamin Zhang, Shiwei Feng, Hui Zhu, Xueqin Gong, Lei Shi, and Chunsheng Guo

***Abstract*—We experimentally investigated how self-heating affected the transient response of drain current in AlGaN/GaN high-electron-mobility transistors. Since drain current depends on temperature, we measured the drain current to assess the transient temperature rise of the active area. Based on the transient temperature rise, we used the structure function method to analyze the resistance to temperature rise. This can be used to extract the chip temperature rise even for a packaged device. We verified the proposed electrical method by comparing its results to those measured by the forward-Schottky-junction-characteristic method, revealing good agreement.**

***Index Terms*—AlGaN/GaN HEMTs, self-heating, drain current transient response, transient temperature rise measurement, reliability.**

I. Introduction

GaN-based high electron mobility transistors (HEMTs) have shown much promise for high-frequency, high-voltage, and high-power applications [1]–[3]. They will play a central role in future telecommunications and radar applications. However, high power dissipation in GaN-based HEMTs can cause substantial self-heating, reducing performance and reliability. Channel temperature enhances phonon scattering, degrading electrical properties [4]–[6], and increases in channel temperature caused by self-heating effect are correlated with decreased device lifetime [7].

Thus, understanding the thermal dynamics of devices has become a key factor for their thermal management. Gathering such time-dependent information in the active area of AlGaN/GaN HEMTs is essential to improving their reliability and performance. One can quantify the self-heating of devices in thermal equilibrium under DC operation from simulations [8]–[10], infrared imaging [11], micro-Raman thermography [12], and other methods. However, there is no way to directly measure the transient temperature, which is unnecessary to prepare special samples. The electrical temperature-sensitive parameter method [13]–[15] is another popular method. The characteristics of forward-biased Schottky junctions depend on temperature, making them useful for measuring transient temperature [16]. However, this measurement cannot be performed during self-heating. Florian *et al.* [17] measured the transient temperature rise of a HEMT active area based on the temperature dependence of its drain current, avoiding the disadvantage of measuring the characteristics of a forward-biased Schottky junction.

In the present paper, we investigate how self-heating affects the transient response of drain current in AlGaN/GaN HEMTs. Using a non-invasive electrical temperature-sensitive parameter method, we detected the transient temperature of the AlGaN/GaN HEMTs, even for devices in a package, using the relationship between temperature and drain current as the sensitive parameter.

II. Temperature Dependence of Drain Current

The single-finger AlGaN/GaN HEMTs samples were grown on SiC substrates by metal-organic chemical vapor deposition (MOCVD). The thicknesses of the intrinsic GaN and $Al_{0.3}Ga_{0.7}N$ layers were 1.5 μm and 25 nm, respectively. The devices had gate lengths and widths of 1.1 μm and 150 μm, respectively. The gate-drain and gate-source spacings were 2.4 μm and 1.5 μm, respectively. The thickness of the SiC substrate was 400 μm. The source and drain were Ohmic contacts. The surfaces of the devices were passivated with 100 nm of Si_3N_4.

The electrical transport properties of semiconductors, such as mobility and electron saturation velocity, are strong functions of temperature [5], [6], [13], [14], [17], [18] and all impact the transient response of drain current. This allows one to estimate the channel temperature induced by self-heating. By measuring the transient drain current, we studied the impact of the channel temperature rise on the transient response of drain current.

The measurements were performed with an Agilent B1500A. The devices under test (DUTs) were placed on a constant-temperature platform at 293 K. The gate voltage (V_{GS}) was maintained at 0 V. Before performing the measurements, we applied a low drain voltage of 0.1 V, low enough to avoid self-heating, for 200 s. The drain voltage was then pulsed from 0.1 V to 10 V. The drain current (I_{D}) was recorded until it reached a steady state. Fig. 1 shows diagrams of the circuit connection and the experimental V_{DS}–I_{DS} procedure.

Trap states depend nonlinearly on the instantaneous drain voltage [19], [20]. Knowing the drain-source voltage (V_{DS}), one can fully determine the presence of traps corresponding to a pulse of positive drain voltage. Moreover, the capture time of GaN traps for positive drain voltage pulses is practically

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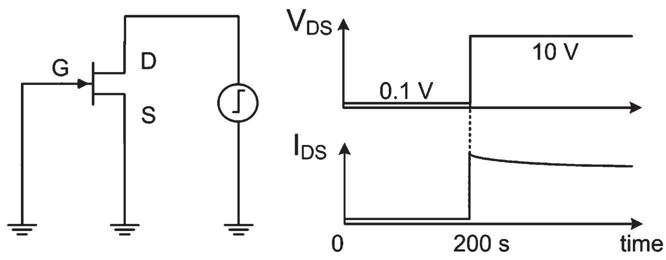

Fig. 1. (Left) Circuit connection and (right) experimental procedure.

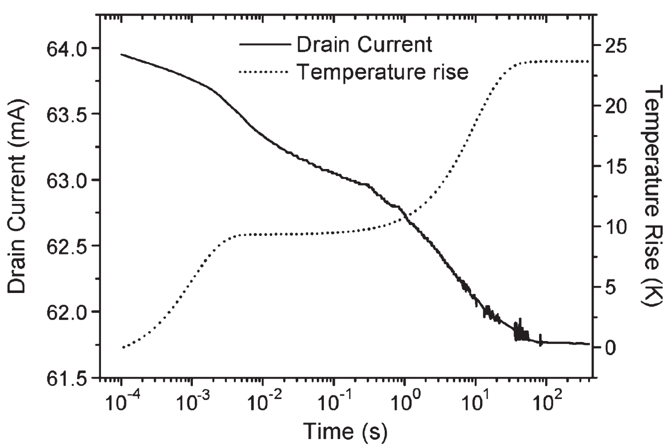

Fig. 2. Changes in channel temperature and drain current with time for $V_{\rm GS} = 0$ V and $V_{\rm DS} = 10$ V.

instantaneous (< 50 ns), as experimentally demonstrated by Florian *et al.* [17] and Santarelli *et al.* [21]. The state of these traps would not change after the $V_{\rm DS}$ reached 10 V. Therefore, at $V_{\rm DS}$ pulsed to 10 V, the transient drain current will only be affected by self-heating.

Based on the electrical temperature-sensitive parameter method [15], [22], the transient temperature rise of channel is measured to verify the standpoint. We selected the forward Schottky junction gate-source voltage $(V_{\rm GSF})$ as the temperature-sensitive parameter. The $V_{\rm GSF}$ shift and the channel temperature change had a linear dependence, which we obtained by recording the $V_{\rm GSF}$ change at different temperatures at $I_G = 300$ μA and $V_{\rm D} = V_{\rm S} = 0$ V. Note that the temperature-sensitive parameter is valid in the forward bias state. Thus, to avoid the breakdown of the device under test (DUT), $V_{\rm DS}$ should be decreased to 0 V before forward-biasing the Schottky junction. $V_{\rm GS} = 0$ V and $V_{\rm DS} = 10$ V were applied to the devices until they reached steady state at a constant channel temperature. Then $V_{\rm DS}$ was turned off and $I_{\rm G} = 300$ μA was applied. The switching time was $\sim$1 μs. The $V_{\rm GSF}$ shifts were sampled at time intervals of 100 μs. Combining the complementary relationship of temperature change in the device heating and cooling, we obtained the transient temperature rise in the channel. Details of this method are presented in our previous work [16], [22]. To ensure recovery of electrical characteristics, all consecutive measurements were separated by 6 h at $V_{\rm DS} = V_{\rm GS} = 0$ V and room temperature [23].

When these measurements were finished, we compared the rise in transient temperature of the channel to the transient response of drain current. Fig. 2 shows the change in channel

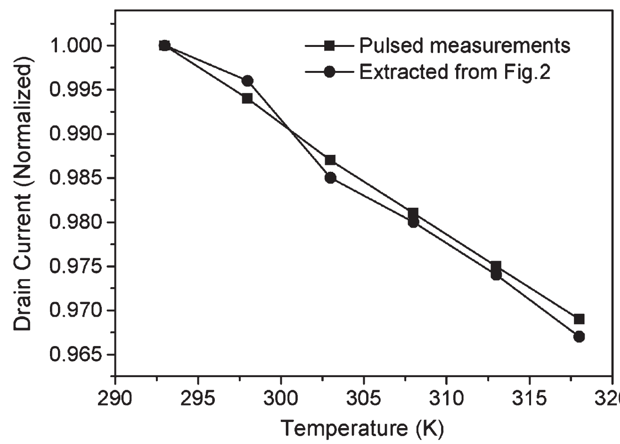

Fig. 3. Drain current versus temperature, extracted from pulsed measurements and from Fig. 2, respectively.

temperature and drain current with time for $V_{\rm GS} = 0$ V and $V_{\rm DS} = 10$ V. The $I_{\rm D}(t)$ curve had two steps, indicating there were more than two factors that caused a drop in the drain current. One step was the rise in the channel temperature with time, which correlated with stepped-down drain current. The time needed to reach steady-state drain current and to reach thermal equilibrium were the same, similar to the results simulated by Miccoli *et al.* [24].

To analyze the temperature dependence of $I_{\rm D}$, we measured the pulsed I–V characteristics, starting at $V_{\rm DS} = V_{\rm GS} = 0$ V at different external temperatures (293–318 K). The pulse width and duty cycle were 1 μs and 0.01%, respectively. Fig. 3 shows the $I_{\rm D}$–T data extracted from the pulsed measurements and from Fig. 2, respectively. As the temperature increased, $I_{\rm D}$ decreased, and they had the same relation. This result indicates that the evolution of drain current was affected only by self-heating, matching experiments by Florian *et al.* [17]. The $I_{\rm D}$ selected to be the temperature-sensitive parameter in this work was suitable.

III. Measurement of Transient Temperature Rise

These measurements consisted of a calibration step and a measurement step. In the calibration step, we measured the temperature coefficient α defined as the change in drain current with temperature. The channel temperature of a device can be changed by external heating or self-heating. In our measurement, we calibrated the temperature dependence of the device parameters through external heating. We placed the device on a constant-temperature platform, used to change the channel temperature. Throughout the experiment, the gate voltage was maintained at a particular value. Before the measurement, we applied a low drain voltage of 0.1 V for 200 s. Then we pulsed the drain voltage from 0.1 V to $V_{\rm DS}$, recording $I_{\rm D}$. The duration of each measurement was very short. The diagram of the circuit connection and procedure for this experiment are the same as those shown in Fig. 1.

Through these experiments, we extracted the maximum $I_{\rm D}$ at different temperatures. Fig. 4 shows the temperature dependence of $I_{\rm D}$, tested on a constant-temperature platform with

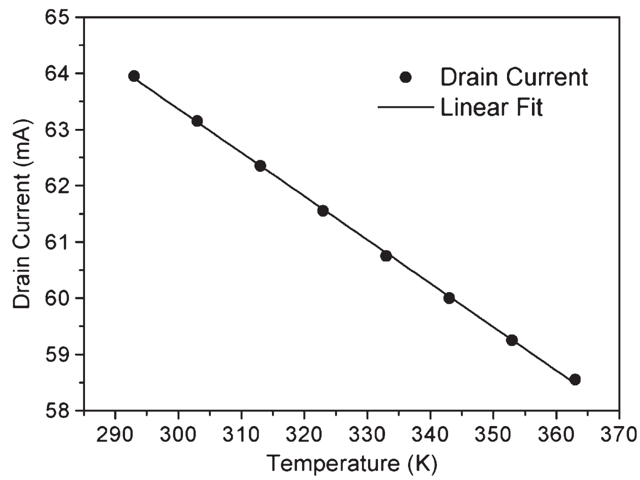

Fig. 4. Calibration curve for AlGaN/GaN HEMT of I_D versus temperature at $V_\mathrm{GS} = 0$ V and $V_\mathrm{DS} = 10$ V.

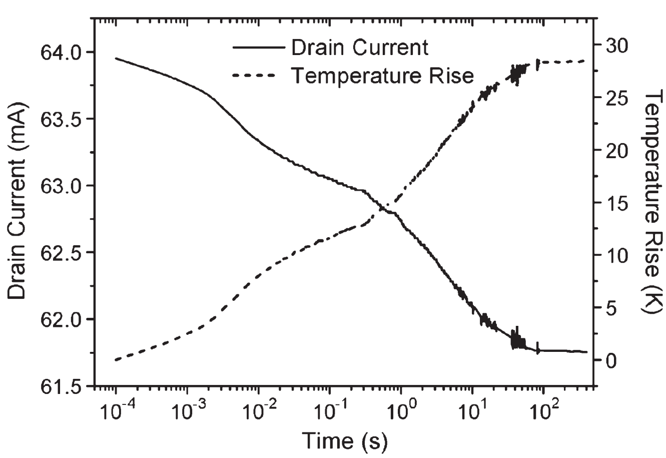

Fig. 5. Change in channel temperature and drain current with time at $V_\mathrm{GS} = 0$ V and $V_\mathrm{DS} = 10$ V, for a device placed on a heat sink.

the temperature accuracy of ± 1 K from 293 K to 363 K. The drain current changed linearly with temperature, allowing us to derive the temperature coefficient α from the linear slope, which we found to be -0.077 mA/K. In this paper, we chose a gate voltage of 0 V. The measurement step was similar to the calibration step, except that I_D was recorded until it reached a steady state. By measuring the temperature coefficient α, the temperature rise of the channel can be obtained by measuring the drain current shift ΔI_D. The transient temperature rise $\Delta T(t)$ can be derived by the following formula:

$$\Delta T(t) = \frac{\Delta I_\mathrm{D}(t)}{\alpha}.$$

Fig. 5 shows channel temperature and drain current with respect to time at $V_\mathrm{GS} = 0$ V and $V_\mathrm{DS} = 10$ V for a device placed on the constant-temperature platform at 293 K. From the drain current shift, we obtained the transient temperature rise of the AlGaN/GaN HEMTs, revealing the temperature rise in the channel to be 26.2 K. This rise of channel temperature with time is similar to the experimental results of Zhang *et al.* [16]. The temperature rise depends on the differences of thermal resistance R_{thi} and thermal capacity C_{thi} between material layers. The temperature can be derived from the following formula:

$$\Delta T(t) = P \times \sum_i R_{thi} \left[1 - \exp(-t/\tau_i)\right]$$

where $\Delta T(t)$ is the temperature rise, P is the power, R_{thi} is the thermal resistance at the ith stage of the Foster RC network, and $\tau_i = R_{thi} \times C_{thi}$ is the time constant. When a device is packaged, the volume of material increases, increasing the thermal capacity and thermal resistance as well as the time needed to heat the material layer. An AlGaN/GaN HEMT can be considered to have two layers, a chip and package, because the AlGaN and GaN layers are so thin. The two time constants we observed differed by more than an order of magnitude, so we consider the curve of the transient temperature rise in the channel to have two steps.

This method we described, which we term the drain-current-characteristic (DCC) method, can be used to not only measure the transient temperature rise of the channel, but can also be applied to analyze thermal resistance. The thermal resistance of the chip $R_{\mathrm{th-chip}}$ and package $R_{\mathrm{th-package}}$ can be extracted from the transient temperature-rise curve using the structure function method proposed by Székely [25]. This method has good vertical resolution, even for a packaged device. Fig. 6 shows the differential structure function of the DUT placed on a heat sink, revealing that $R_{\mathrm{th-chip}}$ was 24.5 K/W and $R_{\mathrm{th-package}}$ was 25.5 K/W.

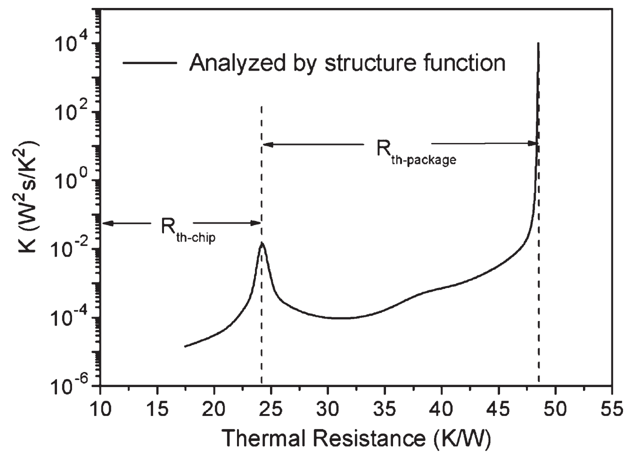

Fig. 6. Differential structure function curve for the AlGaN/GaN HEMTs, used to analyze the thermal resistance.

IV. Discussion

Traps cannot be eliminated, but they can be reduced by surface passivation. If the pulse strategy is not selected carefully, trapping effects can introduce error to these types of transient measurements: for example, if the gate is pulsed instead of the drain. However, because trapping phenomena are almost instantaneous for increasing drain voltages, the trapping state of I_D was practically constant after 50 ns. Because of this behavior, we can consider the evolution of I_D between 50 ns and steady state to only be affected much by thermal effects. Thus,

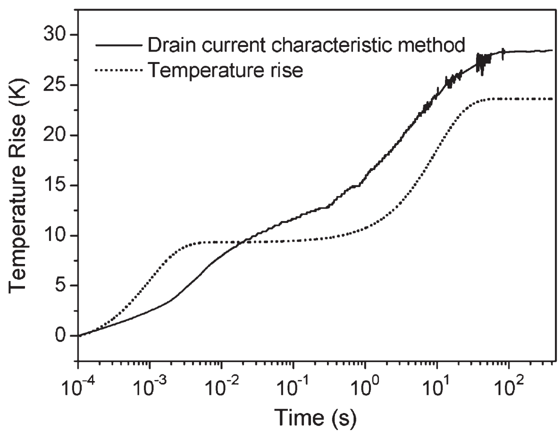

Fig. 7. Transient temperature rise of channel, measured by DCC method and by the FSJC method.

our measurement technique can measure device temperature without influence from traps.

The time constant of the transient drain current drop, induced by the trapping effect, will change with external temperature [26]. To assess this, we recorded the transient drain current following the same method at different temperatures by adjusting the constant-temperature platform. To investigate the effect of trapping, we extracted the time constant from these data, revealing it to be almost identical across all measurements. From these results, we confirm that trapping has little effect.

Fig. 7 shows the channel transient temperature rise, measured by the DCC method and the forward-Schottky-junction-characteristic (FSJC) method. These results show that the two methods measured steps at the same times. Note that the channel temperature measured by the DCC method begins as less than that measured by the FSJC method, then becomes greater.

This difference was caused by heat generated in the gate close to the drain contact, where most of the potential drop occurs in HEMTs [27]. The heat dissipates by thermal diffusion away from the gate close to the drain contact into the substrate. For the DCC method, horizontal heat transport is included in the initial stage. The self-heating duration and measurement period are separated in the FSJC method. The device was first heated to a steady state, and the transient temperature rise was obtained by recording the cooling curve. Horizontal heat transport was not included, so the temperature measured by the DCC method was lower than that measured by the FSJC method first.

The temperature rise measured by the forward Schottky voltage was determined by the distribution of temperature rise in the gate region, which is higher than the mean temperature and lower than the peak temperature. Moreover, the temperature-sensitive parameter is valid for forward bias. Thus, $V_{\rm DS}$ should be turned off before forward-biasing the Schottky junction. The switching time is present, which is another source of measuring error. The mobility and saturation velocity depend on the maximum temperature of channel. These results indicate that the channel temperature measured by DCC method was closer to the peak temperature than that measured by the FSJC method.

V. Conclusion

We demonstrated a method for estimating the channel temperature of GaN-based HEMTs, which can be used to noninvasively probe the transient temperature rise in the channel. The temperature measured by the DCC method was closer to the peak temperature than was the temperature measured by the FSJC method. We observed two steps in the temperature rise as the drain current decreased with time, induced by self-heating. Using the structure function method, we extracted the temperature rise resistance of the AlGaN/GaN HEMTs, allowing us to evaluate the chip temperature rise and thermal resistance of packaged AlGaN/GaN HEMTs.

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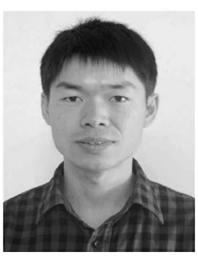

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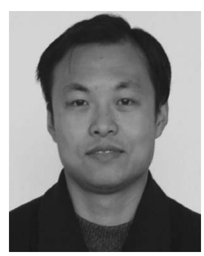

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