Thermal transient testing alternatives for the characterisation of GaN HEMT power devices

Zoltan Sarkany
Siemens DI SW STS
Budapest, Hungary
zoltan.sarkany@siemens.com

Mattia Musolino
STMicroelectronics S.p.A
Catania, Italy
mattia.musolino@st.com

Alessandro Sitta
STMicroelectronics S.p.A
Catania, Italy
alessandro.sitta@st.com

Michele Calabretta
STMicroelectronics S.p.A
Catania, Italy
michele.calabretta@st.com

Nemeth, Mark
Siemens DI SW STS
Budapest, Hungary
mark.nemeth@siemens.com

Gabor Farkas
Siemens DI SW STS
Budapest, Hungary
gabor.farkas@siemens.com

Marta Rencz
Siemens DI SW STS
Budapest, Hungary
marta.rencz@siemens.com

Abstract—**Despite all the advancements, thermal characterization of GaN HEMT devices is still a challenging task today. In this paper we present a new transient measurement approach utilizing the gate current as temperature sensitive electric parameter (TSEP) and compare the results to the data captured using the channel resistance (V_{ds}). The experienced differences are small, but repeatable. We examine the various factors that could cause artifacts in each method, but no evidence of measurement error was found.**

Keywords—GaN, HEMT, thermal transient testing

I. INTRODUCTION

In the last few years, Gallium Nitride (GaN) based power transistors are quickly emerging on the market with many different applications, from high-frequency amplifiers for telecommunication to low power converters for consumer electronics, and it is forecasted that in the next years the GaN devices market share will grow further [1]. To enter the market the new GaN products need to pass many stress tests. One of the critical figures of merit that must be monitored during these tests is the T_J junction temperature. This parameter is also fundamental to optimize the thermal resistance (R_{th}) of the package and to exploit at best the high operating temperature and the high-power density of the GaN HEMT technology.

Among the different ways to estimate the junction temperature of the device (e.g., contact methods, optical methods, integrated sensors, simulations etc.), the one based on a Temperature Sensitive Electrical Parameter (TSEP) is the most used for reliability tests. It exploits an intrinsic property of the device, thus providing a non-destructive, fast, and accurate method to measure the temperature very close to the junction without the need of external tools or additional integrated components. Depending on the HEMT structure, the channel resistance R_{on} or the gate-source voltage V_{GS} have been proposed as TSEP [2][3]. However, the best approach has not been defined yet, and it might depend on the characteristic of the device (i.e., gate properties, R_{on} value etc.). Each TSEP has their advantages, disadvantages, and optimal application conditions and the proper one shall be selected for the actual application.

The R_{on} parameter is proportional to the temperature conditions along the whole device channel and hence it can be a good indicator of its average temperature. However, in case of low channel resistance a high measurement current is required to generate sufficient amplitude of temperature dependent voltage signal. This high measurement current can generate significant amount of power and limit the achievable power step size between the heating and cooling stages. E.g., for a device with 1mΩ channel resistance a 10-20A of measurement current would be required to generate 10-20mV signal even at large temperature changes.

The Gate-source voltage V_{GS} can be used especially well in case of devices with classic, d-mode characteristic devices with Schottky contact between the gate and the channel. In these cases, a very small measurement current (even below 1mA) is sufficient to bias the contact and ensure a signal with low noise and high temperature dependence. The applicability of this method however is compromised by the modified gate structures and increased HEMT threshold voltages. More modern switching mode optimized HEMT devices often have enhancement mode characteristics, where the gate current at the 5-6V nominal gate voltage levels is significantly reduced. As a result, the application would demand very small, only a few tens of microamps range of measurement currents and would result in tens of kiloohms of source impedance. The result of all these is extremely high measurement noise, that can make the measurement impossible.

In this work, the gate-source current I_{GS} is proposed as an alternative TSEP for HEMTs with junction gate structure (p-n or Schottky) or even with Ohmic contact. The I_{GS} measurement method is presented and is compared to the R_{on} TSEP and the experienced differences are examined in more depth.

For all the measurements presented below a power HEMT from STMicroelectronics was used.

II. METHODOLOGY

To maximize the fidelity of the comparison between the two measurement methods the two selected TSEP signals were captured concurrently using the measurement setup shown in Figure 1.

The HEMT device is turned on via the DC voltage source (V_{GS}) through a current sense resistor (R_s). For most of the measurements a precision, low noise fixed 5V voltage source was used, to maximize the measurement accuracy. Considering the low gate current level of the tested device (<25µA) the voltage drop on the R_s resistor was amplified by an instrumental amplifier before the connecting it to the T3Stersystemfor transient measurement. After several experiments Rs was selected to be 250Ω, and the amplification was set to approximately x25 (x24.4 actual amplification) resulting in approximately 0.63nA current resolution.

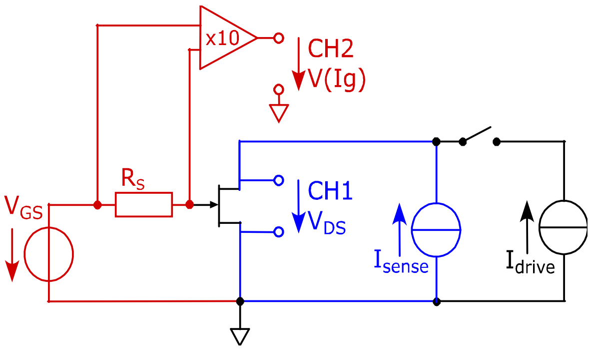

Figure 1- HEMT measurement setup combining channel resistance and gate current measurement approaches

For the measurement of the channel resistance an I_{sense} sense current generator was supplying the drain current during the cooling and the voltage drop was measured by a transient measurement channel directly. Considering the ~70mΩ channel resistance 1A was selected as sense current, which generated approximately 70mV voltage drop at cold state. For the heating, an additional I_{drive} current source was connected on the drain through a fast switch to allow quickly turning off the heating.

The surface mounted HEMT sample was soldered to a high conductivity PCB board. To minimize the thermal resistance and ensure short thermal transient settling time the bottom side of the PCB board was forced to a water cooled aluminium cold plate through a copper spacer. The copper spacer was necessary because of the trough hole pins soldered into the test board. Electrically insulating thermal pad was put between all contacting surfaces. A schematic drawing of the measurement setup can be seen in Figure 2.

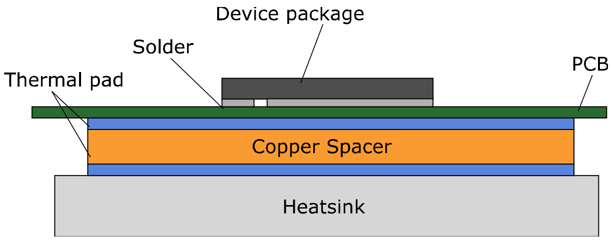

Figure 2 – HEMT device package mounted on PCB and pushed to a heat sink with a copper spacer.

The test PCB contained separately routed sense pins for both the source and drain connections of the package to support four wire measurements, but preliminary experiments showed inconsistent measurement results and hence additional sense wires were soldered directly to the drain and gate contacts of the package (0.1mm insulated copper wires). All measurement results presented were measured using this optimized four wire measurement method.

All measurements were carried out with the cold plate set to 25°C.

The TSEPs were calibrated in the above-described setup between 20 and 85°C in 5°C steps. After setting the next temperature point, we waited until the temperature properly stabilized before the DUT voltages were registered. This fine calibration was necessary because of the nonlinear temperature dependence of the measured voltage parameters. The calibration curves are shown in Figure 3. As it can be seen the 5th order polynomial curves fit well on the measured points (R^2=1), these curves were used for the voltage to temperature conversion in all measurements (where applicable).

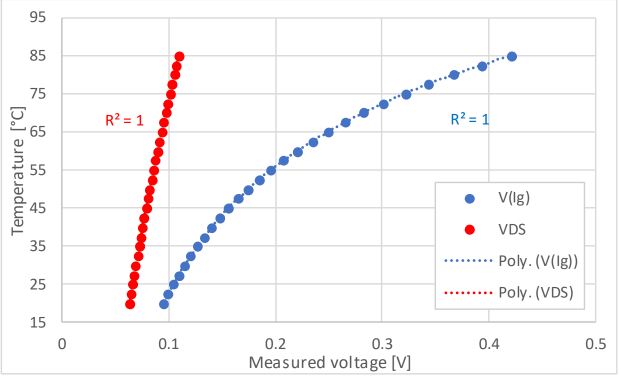

Figure 3 – Temperature sensitivity calibration curves with fitted 5th order polynomial trendlines

III. RESULTS AND DISCUSSION

A. Comparison of the two transients

The measurement was run using the measurement setup described in the previous section using 5A as heating current with 360s of heating and cooling times to allow proper stabilization of the temperature. The transient results are shown in Figure 4. Both transient responses show good noise characteristic and seem to have short initial electric transient. After about 50 microseconds both curves show monotonously decreasing temperatures, and the measured total temperature elevation was approximately 20°C in both cases. However, the two concurrently captured curves show differences in their time functions and do not match perfectly.

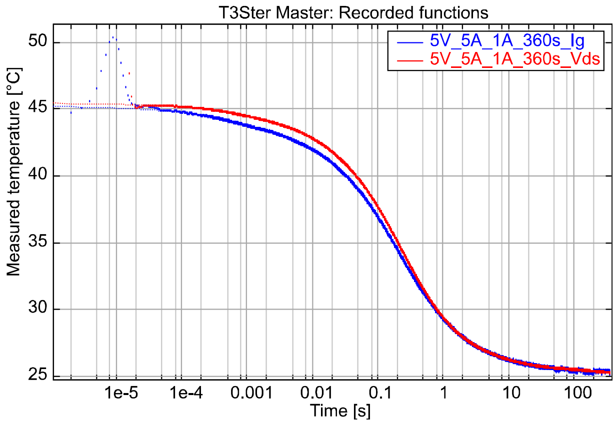

Figure 4 – Thermal transient response captured concurrently using the two different TSEP parameters

An often-used test to validate if a measurement is purely thermal or distorted by secondary electrical effects is to repeat the measurement with several different heating current levels. A purely thermal signal assuming linear system scales with the power dissipated by the component and hence the Zth curves should overlap. We repeated the transient measurement at 4A to 7A in 1A steps, and the resulting structure functions are shown in Figure 5. We can see two groups of curves corresponding to the two TSEPs we measured. The curves in each group show very good fit, not indicating any obvious problems.

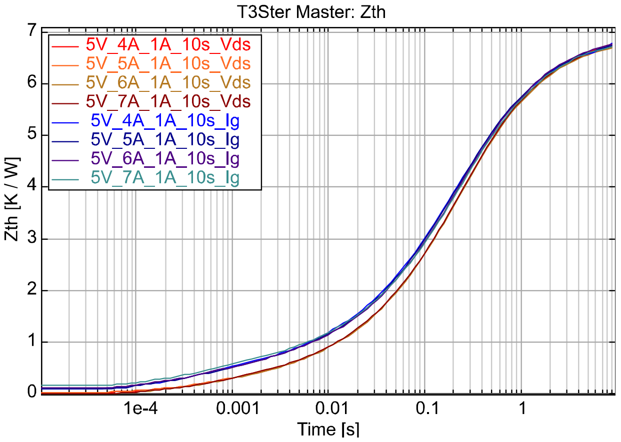

Figure 5 – Zth curves captured at 4A, 5A, 6A and 7A heating current levels, fitted at the hot end

Based on the above test, without the control measurement to compare with, we could accept any of the two transients as valid Zth curves. In practical application, for cooling design purposes the difference of the measured thermal resistances is acceptable. However, for structure analysis the differences must be better understood. We found that the transient curves can be overlapped perfectly after about 5-10 milliseconds with a constant multiplier of 1.058. However, the early section of the curve remains different. This difference in the early transient can be interpreted as the result of the fact that the two temperature sensitive parameters are proportional to the temperature of slightly different regions of the HEMT structure. This can cause a difference in the early transient, but not in the transient section corresponding to the environment. Due to the high conductivity of the semiconductor material, the temperature gradients on the chip surface should even out in a relatively short time. Assuming this is the real transient temperature change, the question remains, why is there a ~6% difference in transient amplitude.

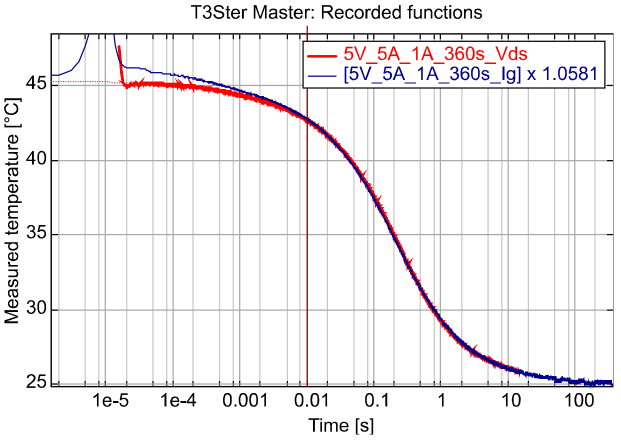

Figure 6 – Raw thermal transient response curves, fitted between 10ms and 360s with constant multiplier (1.058)

B. *Effect of TSEP calibration*

One possible source of proportional error is the improper temperature sensitivity calibration. We repeated the automated calibration several times with different parameters and did manual calibration as well, but no larger than 1% of difference in the measured data could be observed.

In most transient tests the sense current is very small, and hence the power dissipation during the cooling transient (and the calibration) is negligible. In case of the actual measurement the sense current was selected to be 1A, which resulted in about 0.07W of dissipation at 25°C and 0.1W at 85°C. Considering the total junction to ambient R_{th} is approximately 7 K/W according to the Zth curve shown in Figure 5, the junction temperature has to be 0.5-0.7°C hotter than the set baseplate temperature. Adding this compensation to the calibration curves had no significant effect on the results.

C. *Examination of the I_G current transient*

As a next step we attempted to validate the gate current measurement. We used a serially connected sampling multimeter (Keithley DMM7510) to capture the gate current signal during the transient measurement with a 50 sample/sec sampling rate. After synchronizing the two signals in time the measurement results fit perfectly as it is shown in Figure 7.

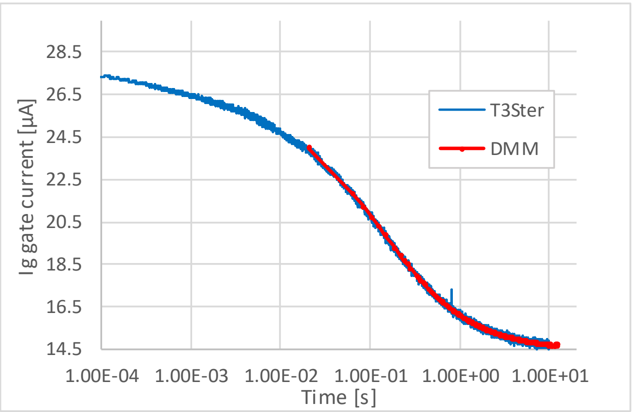

Figure 7 – comparison of gate current measured by T3Ster (blue) and multimeter (Keithley DMM7510, red)

To use it for temperature measurement we assumed that the gate current is only dependent on the temperature if we keep the gate voltage constant. However due to the changing drain voltage a capacitive displacement current can flow as well, which distorts the thermal transient response. This displacement current can be calculated as

$$i_d(t) = C_{GC}\frac{d(V_G - V_{CH})}{dt}, \qquad 1)$$

where i_d is the displacement current, C_{GC} is the gate to channel capacitance, V_G is the constant gate voltage and V_{CH} is the average voltage of the HEMT channel, which can be approximated by $V_{DS}/2$. In Figure 8 the measured gate current (blue) and the gate current compensated by the displacement current (green) are compared. Significant difference can only be observed at the initial electrical transient of the V_{DS} voltage (red) changing from the higher current operating point (heating) to the lower current level (cooling). The C_{GC} capacitance value was selected to 112pF to best compensate the peak on the gate current curve. This capacitance is in good agreement with the 120pF input capacitance provided in the datasheet of the HEMT. Above 20µs the capacitive current was negligible, below 0.01% of the total gate current.

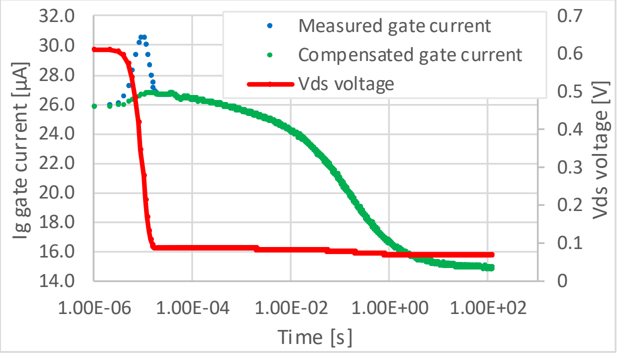

Figure 8 – Effect of displacement current through the capacitor

When we had a closer look at the transient curve of the gate current especially in linear time scale, we could clearly observe a series of jumps in the signal as it is shown in Figure 9 on the top graph. To verify if this phenomenon is an artifact generated by our transient measurement setup, we used a Keithley 2450 source meter unit to characterize the gate current. The SMU was set to supply fixed 5V gate voltage, and the gate current was measured. Even with the T3Ster and chiller completely disconnected and turned off we experienced similar stepwise current changes like before, with an amplitude of about 40nA (see Figure 9, bottom graph). As this artifact is not generated by our transient measurement setup and its small amplitude cannot be responsible for the difference of the transients measured with the two different TSEPs we ignored this effect in our investigation.

Overall, we found that the measurement setup we used for the gate current measurement provides accurate measurement results and found no distorting effects in the relevant time domain above 50µs.

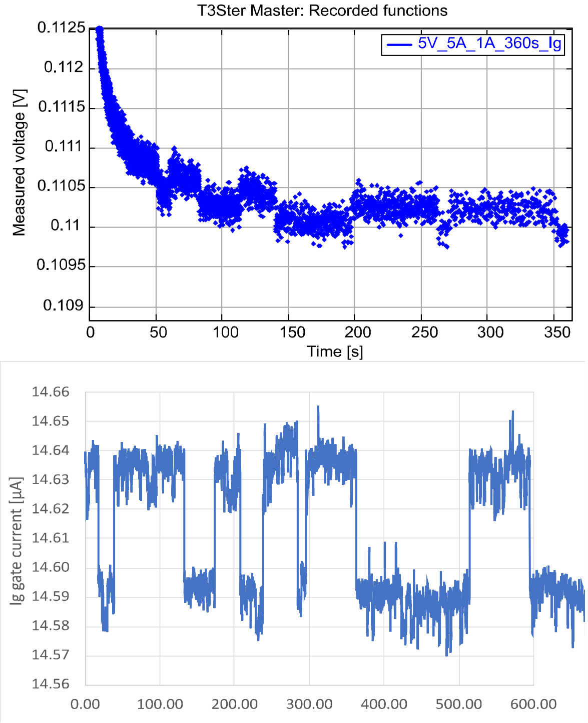

Figure 9 – Stepwise current changes in gate current measured with T3Ster (top) and with Keithley 2450 SMU (bottom)

D. Examination of the V_{DS} transient

After we found no evidence of error in the gate current measurement, we examined the V_{DS} measurement as well. In the initial experiments we found that the drain and source sense points on the panel did not provide adequate four wire measurement results and had to use thin wires connected directly to the package to measure consistent data.

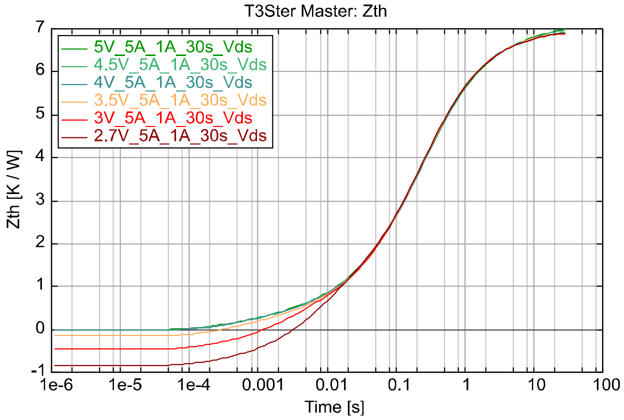

Figure 10 – Effect of gate voltage on V_{DS} transient

To check if the remaining serial resistances (inside and outside of the package) can still cause distortions in the measured voltage, we repeated the measurement with different gate voltage levels. The decreasing gate voltage increases the channel resistance and hence changes the ratio between the channel resistance and the serial resistances. The Zth curves of the measured transients are shown in Figure 10 fitted at the end corresponding to the environment. Until 4V, no difference could be observed, but further decreasing the gate voltage induced an increased temperature change (transient amplitude) at the beginning of the curve, up to about 20 milliseconds. This effect is likely to be caused by hot spot formation on the chip surface that diminishes until 20µs. No sign of changes in the latter transient sections were observed.

IV. CONCLUSIONS

In this paper we presented a new thermal transient measurement method utilizing the gate current as temperature sensitive parameter and compared its result to the well-established channel resistance measurement.

The two measurement results showed a small, ~6% difference, acceptable for junction to ambient measurement purposes, but not adequate for structural analysis.

Examining the various possible error sources, temperature sensitivity calibration, electrical distortions of gate current measurement and V_{DS} measurement we found no evidence of measurement error above 50µs.

To find the source of the difference further investigations are required.

REFERENCES

[1] OMDIA 2021 https://omdia.tech.informa.com/OM007030/GaN--SiC-power-semiconductor-markets-set-to-pass-1-billion-mark-in-2021

[2] Z. Sárkány et al., "Thermal transient characterization of pHEMT devices," in 18th International Workshop on Thermal Investigation of ICs and Systems, Budapest (2012), pp. 1-4.

[3] Shan et al., "Test methods and principles of thermal resistance for GaN HEMT power devices" in 21st International Conference on Electronic Packaging Technology (2020).