Accurate Measurement of Dynamic ON-Resistance in GaN Transistors at Steady-State

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***Abstract*—Accurate characterization of the dynamic ON-resistance (R_{ON}) degradation is important to predict conduction losses for gallium nitride high-electron-mobility transistors (GaN HEMTs). However, even for the same device, many inconsistent results of dynamic R_{ON} based on pulsed measurements are reported in the literature. This letter reveals that insufficient test time leads to spurious dynamic R_{ON} results and even contradictory conclusions. We show that the time required for the dynamic R_{ON} to stabilize can be very long (~ 3 mins) for some commercial GaN devices and pulsed measurements fail to give accurate results. These findings are enabled by our proposed steady-state method using a hard-switching half-bridge with an active measurement circuit. It minimizes the influence of temperature on the R_{ON}, enabling to capture trap-related effects independently from the operation conditions. This work raises awareness of the effect of poorly measured dynamic R_{ON} and highlights that steady-state methods should be applied for accurate measurements to predict their performance in real power converter operations.**

***Index Terms*—Conduction losses, dynamic ON-resistance, gallium nitride, power transistor, steady-state measurement**

I. INTRODUCTION

Gallium nitride high-electron-mobility transistors (GaN HEMTs) are promising for next-generation power conversion thanks to their excellent properties, enabling high switching speed and low specific on-resistance [1]. However, they often suffer from dynamic ON-resistance (R_{ON}) degradation, where R_{ON} increases right after the device turn-on due to electron trapping phenomena. Electrons can get trapped either in the buffer and/or on the surface under high electric fields during the OFF-state [2], [3], and during hard-switching transients (as hot-electron trapping [4]). This results in higher conduction losses and has been a major concern in GaN power switching.

Most of the measurement methods found in the literature to characterize dynamic R_{ON} are based on different forms of pulsed measurements, e.g., with a single pulse stress [5], double pulses [6-10], and multiple pulses [7-9]. In these methods, a short test time (in the range of μs) is applied to avoid self-heating, as temperature also has an effect on the R_{ON} increase. However, results for identical devices are often very different and even sometimes conflicting in these studies. Fig. 1 compares the dynamic R_{ON} values from the literature with different measurement techniques applied to an identical GaN device (GS66508B/T) under hard-switching conditions. Large discrepancies in the dynamic R_{ON} increase can be observed, e.g., from 7% to 55% at an OFF-state voltage ($V_{ds(OFF)}$) of 400 V. Furthermore, results in [7] show a monotonic dependence on $V_{ds(OFF)}$ while those in [5] and [6] show a non-monotonic voltage dependence. These discrepancies could be attributed to the short test time, as it was observed that the trapping-related carrier transport time constants in the buffer can be on the order of seconds [2], [3], [11]. Insufficient test time fails to capture effects from any possible large trapping time constants, which, however, are seen in steady-state operations. Another factor that may give rise to the reported dynamic R_{ON} variations is the OFF-state bias time before pulsed tests, which may induce extra OFF-state trapping but is not always described, e.g., in [5] and [6] but not in [7]. These pre-stress conditions, nevertheless, are not representative of real power converter operations at steady-state.

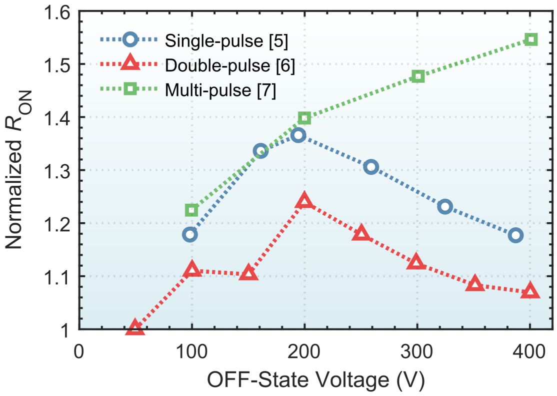

Fig. 1. Previously reported dynamic R_{ON} for an identical GaN HEMT (GS66508B/T) under hard-switching conditions. Significant discrepancies in dynamic R_{ON} values and behaviors can be observed.

Without consistent measurements, the significance of dynamic R_{ON} degradation remains unclear and a fair comparison between different GaN technologies is impossible. So far, only very few studies applied steady-state approaches to evaluate dynamic R_{ON}, e.g., in a Buck converter [12]. However, a full-power converter exhibits significant device losses and rises in device temperature, which also have an effect on R_{ON}. Therefore, distinguishing trapping-related time constants from thermal time constants in these methods is very challenging. This is important as studies in [9] and [10] show that the behavior of dynamic R_{ON} versus $V_{ds(OFF)}$ can vary significantly with temperature, which might be a source of inconsistencies when comparing different devices if the temperature is not controlled and unknown.

In this letter, we show that some commercial GaN devices exhibit very slow transients before the dynamic R_{ON} stabilizes (up to 3 mins), and we reveal that insufficient test time can lead to spurious results and contradictory conclusions. These findings are

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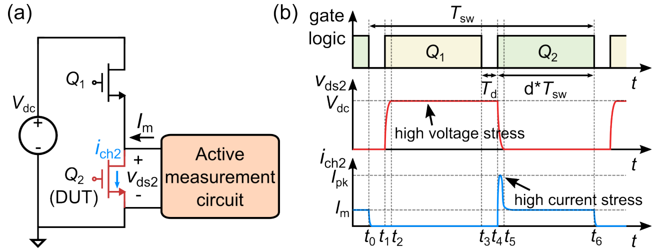

Fig. 2. (a) Schematic of the proposed half-bridge no-load circuit with the low-side transistor Q_2 as the device-under-test (DUT). A measuring current (I_m) is injected from the active measurement circuit to monitor the ON-state voltage of the DUT. (b) Gate control signals of the half-bridge and related waveforms of the drain-source voltage (v_{ds2}) and channel current (i_{ch2}) of the DUT. Q_1 and Q_2 are switched complementarily at steady-state. The R_{ON} of Q_2 is measured during t_5-t_6 immediately after the hard-switching transient (t_4-t_5).

enabled by our proposed steady-state method using a hard-switching half-bridge with an active measurement circuit, which minimizes device losses and temperature rise even with steady-state operations. This work highlights the need for steady-state measurements to accurately characterize the dynamic R_{ON} of GaN devices and provide a pathway toward a clearer identification and a fair comparison of dynamic R_{ON} between different technologies.

II. METHODOLOGY

A. *Operation Principles*

Fig. 2(a) illustrates the proposed circuit for investigating the dynamic R_{ON} degradation at steady-state. The low-side device Q_2 in the half-bridge circuit is the device-under-test (DUT). Instead of using an inductive or resistive load current I_L to measure R_{ON} when Q_2 is on, a measuring current I_m is injected from the active measurement circuit during the ON-time. Detailed operation modes are shown in Fig. 2(b). Before switching, Q_2 is kept on and its static dc ON-resistance (R_{dc}) is examined to ensure that there is no residual trapping effect from previous tests. Then after t_0, Q_1 and Q_2 start to switch complementarily in continuous mode at a switching frequency of f_{sw}. Within one period, Q_2 is biased with V_{dc} during the OFF-state (t_2-t_4) and then experiences a hard turn-on event (t_4-t_5). During the hard-switching transient, the channel current i_{ch2} of Q_2 reaches its peak I_{pk}, which is considerably high due to the fast discharging of the DUT output capacitance and charging of the output capacitance of Q_1.

This operation mode imposes high voltage and high switching current stress on the DUT, allowing one to investigate the effect of both OFF-state trapping and hot-electron trapping on dynamic R_{ON} degradation. On the other hand, the no-load circuit features minimal device losses and temperature rises even at steady-state. The hard-switching losses (P_{sw}) can be modeled as a quadratic function of the external load current I_L [13] as

$$P_{\mathrm{sw}} = (a + bI_{\mathrm{L}} + cI_{\mathrm{L}}^2)f_{\mathrm{sw}} \tag{1}$$

where $a = Q_{\mathrm{o}}V_{\mathrm{dc}}$ with Q_o the device output charge, and b and c are switch-dependent coefficients. By operating at no-load conditions ($I_L = 0$), switching losses are minimized and conduction losses (P_{con}) are only induced by the measuring current I_m, which is much smaller than with external load current. Assuming negligible gate losses, the total losses (P_{total}) of the DUT can be derived as follows

$$P_{\mathrm{total}} = P_{\mathrm{con}} + P_{\mathrm{sw}} = d\, I_m^2 R_{\mathrm{ON}} + Q_{\mathrm{o}} V_{\mathrm{in}} f_{\mathrm{sw}}. \tag{2}$$

where d is the duty cycle of the DUT. Device losses can be further reduced with a low f_{sw}. By minimizing the device temperature rise, the R_{ON} increase is solely due to the trapping effect, which can be distinguished from thermal effects.

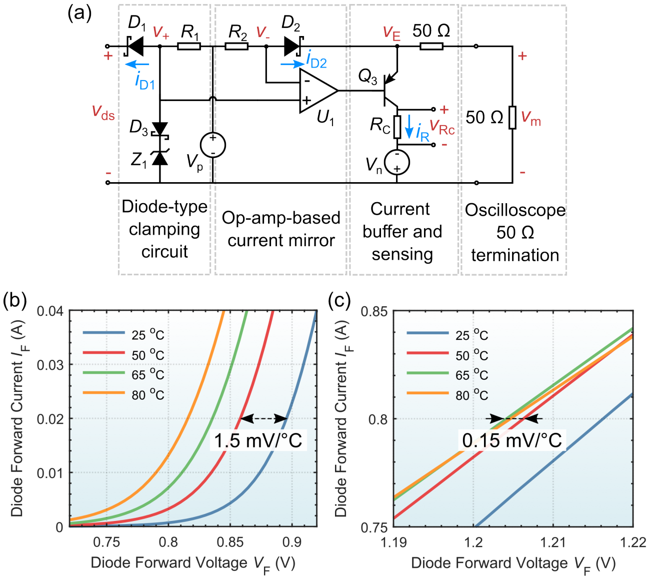

Fig. 3. (a) Schematic of the active measurement circuit featuring OFF-state voltage blocking, diode voltage compensation, current sensing, and 50 Ω output impedance. The blocking diode (i.e., D_1) shows significantly different temperature-dependent forward characteristics: (b) at low current levels (~20 mA): 1.5 mV/°C and (c) at high current levels (~800mA): 0.15 mV/°C.

Moreover, this measurement method is independent of the type of load, which can reveal some intrinsic R_{ON} degradation from the devices, regardless of the type of load used. It also offers a possibility to independently investigate the additional degradation that different loads might induce in GaN devices.

B. *Design of the Active Measurement Circuit*

Here we revisit the design of ON-state voltage measurement circuits (OVMC) and propose an active measurement circuit to implement the measurement concept.

In principle, an OVMC blocks the high OFF-state voltage and allows measuring the ON-state voltage of the DUT with high resolution, soon after the switching transient. Diode-type clamping circuits have been widely used because of the low parasitic capacitance of the blocking diode [5]-[7], [10]. Typically, the diode forward current, which also flows to the DUT, is tuned to be small (e.g., ~20 mA) to avoid heating up the blocking diode, because the measurement accuracy relies on offsetting the diode forward voltage, but unfortunately, this parameter is temperature-dependent. Researchers have also proposed to use a second diode and achieve diode voltage drop compensation with an operational amplifier (op-amp) [12], [14], but still, it is challenging to maintain an even temperature distribution and a voltage match for the diodes.

By leveraging insights from prior work [7], [12], [14], we propose an active measurement circuit as shown in Fig. 3(a) to address the above-mentioned challenges. D_1 and D_2 are two identical SiC Schottky diodes (GB01SLT06-214). When the DUT is turned off, D_1 blocks the OFF-state voltage and v_+ is

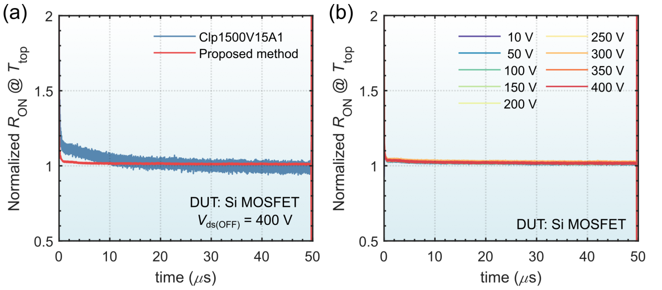

Fig. 4. Time-resolved waveforms of R_{ON} normalized to $R_{dc}(T_{top})$ of the Si DUT under steady-state conditions, with f_{sw} = 10 kHz, d = 50%, $V_{g(ON)}$ = 10 V, $R_{g(ON)}$ = 47 Ω. (a) Comparison between a commercial voltage clipper (Clp1500V15A1) and our proposed method. The former exhibits a settling time in the range of 10 μs, which limits its use at higher frequencies. (b) Normalized R_{ON} waveforms at different OFF-state voltages for the Si DUT, confirming no degradation in dynamic R_{ON} for all blocking voltages, as expected.

clamped by the clipping branch made of a low-voltage Schottky diode D_3 (SS12) and a Zener diode Z_1 (1SMA5913BT3G). When the DUT is turned on, the diode forward current i_{D1}, which also goes through the DUT, is designed to be considerably higher than in existing clamping circuits, e.g., around 800 mA with V_p = 3.3 V and R_1 = 2.5 Ω. Diode voltage compensation is achieved by the feedback control of a high-speed op-amp U_1 (AD8045) to achieve $v_- = v_+$ and by having $R_2 = R_1$ as discussed in [14]. Therefore, $i_{D2} = i_{D1}$, and from symmetry, we obtain $v_E = v_{ds}$. The ON-state voltage of the DUT is then measured by the 50 Ω termination of the oscilloscope input as

$$v_{\mathrm{ds}} = v_{\mathrm{E}} = 2v_{\mathrm{m}}\,. \tag{3}$$

To handle the large current i_{D2} in the Op-amp-based current mirror, we incorporated a current buffer that consists of a PNP bipolar junction transistor Q$_3$ (PBSS5240X), a sensing resistor R_C = 3.3 Ω, and a voltage source V_n = 3.3 V. The collector current i_R of Q$_3$ is identical to the diode currents as the base current of Q$_3$ and the current into the oscilloscope input are negligible. Therefore, the injected current into the DUT can be monitored by measuring v_{Rc} as

$$i_{\mathrm{DUT}} = i_{\mathrm{D1}} = i_{\mathrm{D2}} = i_{\mathrm{R}} = \frac{v_{\mathrm{Rc}}}{R_{\mathrm{C}}}, \tag{4}$$

and the real-time R_{ON} can be calculated as follows

$$R_{\mathrm{ON}} = \frac{v_{\mathrm{ds}}}{i_{\mathrm{DUT}}} = \frac{2v_{\mathrm{m}}R_{\mathrm{C}}}{v_{\mathrm{Rc}}}. \tag{5}$$

As shown in (5), the proposed measurement method only relies on two simple voltage measurements, v_m and v_{Rc}. The *I-V* characteristics of diodes are only measured once to find two diodes (D_1 and D_2) exhibiting the closest voltage drop. This method eliminates the need for diode voltage drop offsetting in postprocessing since voltage compensation is implemented in real-time measurements.

By tuning the operation point at higher current levels, the diode voltage drop is much less sensitive to temperature variances as shown in Fig. 3(b) and (c). For example, the temperature coefficient of the SiC Schottky diode used is 1.5 mV/ºC at 20 mA and 0.15 mV/ºC at 800 mA measured with a B1505 semiconductor analyzer. Hence a much better diode voltage match and compensation can be achieved. Also, a high forward current accelerates the discharge of the diode parasitic capacitance during the turn-on transient and thus enables fast transient responses.

C. *Validation with Si MOSFET*

The proposed method also benefits from the 50 Ω output impedance, which provides impedance matching with cables and 50 Ω input termination of the oscilloscope. This is important because it allows a flat gain for all the frequency responses, minimizes signal reflection, and presents the least settling effect. Conventional voltage clippers use high input impedance voltage probes (e.g., TPP1000 1 GHz passive probe from Tektronix), which exhibit undesirable long settling time that may be misinterpreted as dynamic R_{ON} degradation effects, even when testing a Si MOSFET.

In order to verify and justify our method before testing GaN HEMTs, we used a bottom-side cooled Si MOSFET (STL26N60DM6, 600 V/15 A) to benchmark our method, and compare the results with a commercial voltage clipper (Clp1500V15A1). The test conditions were as follows: switching frequency f_{sw} = 10 kHz, duty cycle d = 50%, gate drive voltage $V_{g(ON)}$ = 10 V, and gate turn-on resistor $R_{g(ON)}$ = 47 Ω. The results were normalized to the R_{dc} obtained from 4-wire dc measurements at the corresponding top surface temperatures (T_{top}), which were monitored with an infrared camera (Fluke TiS65). Fig. 4(a) shows that the commercial voltage clipper suffers from a long settling time and low resolution, mainly due to the use of high-impedance termination and large vertical division setting of the oscilloscope. The long settling time, in the range of 10 μs, limits its use at higher switching frequencies, while the proposed method shows nearly zero settling time and higher resolution thanks to 50 Ω matching impedance. Fig. 4(b) shows the expected absence of dynamic R_{ON} degradation at different $V_{ds(OFF)}$ for the Si DUT and reveals the high fidelity of the measurements, validating our method.

III. MULTIPLE PULSES ARE NOT ENOUGH IN DYNAMIC R_{ON} MEASUREMENTS

The proposed method was used to investigate the dynamic R_{ON} behavior of a commercial Schottky-type *p*-GaN gate HEMT (GS66502B, 650 V/7.5 A) at steady-state.

The GaN DUT is bottom-side cooled and its top surface temperature T_{top} was monitored. Instead of studying the effect of temperature on dynamic R_{ON} degradation, here we aimed to exclude the temperature effects since temperature rises also have an effect on the R_{ON} increase and dynamic R_{ON} versus $V_{ds(OFF)}$, as shown in [2], [9], and [10]. We first chose a low switching frequency, i.e., 10 kHz, that led to negligible switching losses, and measured T_{top} remained almost unchanged (26 °C – 27 °C) for all $V_{ds(OFF)}$ at steady-state. In this way, the dynamic R_{ON} increase, due solely to electron trapping, can be measured and trapping-related time constants can be distinguished from other effects.

Fig. 5(a) shows the half-bridge circuit with the GaN DUT and the active measurement circuit, mounted close to the DUT to minimize interconnection parasitics. Fig. 5(b) shows the dynamic response of the measurement circuit where the measured voltage v_m quickly settles in less than 100 ns after the DUT is turned on. The fast dynamic response is crucial as GaN transistors are able to operate at high switching frequencies with a short ON-time for measurements. Fig. 5(c) shows the steady-state R_{ON} waveforms

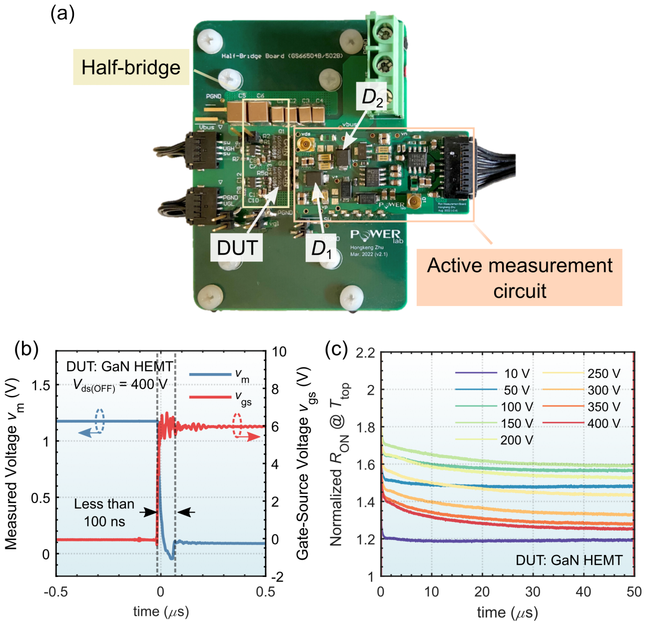

Fig. 5. (a) Hardware implementation of the half-bridge circuit board with the GaN DUT and the active measurement circuit. (b) Dynamic response of the measurement circuit when testing with the GaN DUT. v_m quickly settles in less than 100 ns before the ON-state voltage is monitored. (c) Time-resolved waveforms of the dynamic R_{ON} normalized to $R_{dc}(T_{top})$ of the GaN DUT under steady-state conditions at different $V_{ds(OFF)}$, with f_{sw} = 10 kHz, d = 50%, $V_{g(ON)}$ = 6 V, $R_{g(ON)}$ = 10 Ω. At such conditions, the steady-state temperature of the DUT remains substantially unchanged (26 °C – 27 °C) because of the negligible switching and conduction losses.

during the ON-time at different $V_{ds(OFF)}$ with f_{sw} = 10 kHz, d = 50%, $V_{g(ON)}$ = 6 V, $R_{g(ON)}$ = 10 Ω. Results are normalized to the R_{dc} at the corresponding T_{top}. From Fig. 5(c), it can be seen that the investigated GaN DUT exhibits a notable increase in dynamic R_{ON} with $V_{ds(OFF)}$, which peaks between 100V and 200V. A de-trapping pattern during the first 40 μs of the ON-time starts to appear when $V_{ds(OFF)}$ > 50 V and becomes more obvious with higher $V_{ds(OFF)}$. Interestingly, there is a considerable increase of 20% in R_{ON} even at $V_{ds(OFF)}$ = 10 V. This could be attributed to gate-stress-induced V_{th} shift [15], and/or buffer trapping which is also observed at a low OFF-state voltage $V_{ds(OFF)}$ = 25 V [3].

These new findings for this type of GaN device can only be captured at steady-state due to large trapping time constants that were observed on the order of 1 – 100 s. To put it in perspective, real-time R_{ON} waveforms were recorded before, during, and after switching at 10 kHz for a period of 5 mins with $V_{ds(OFF)}$ = 100 V and 400 V respectively as shown in Fig. 6(a) and (b). A low sample rate of 50 kS/s and high-resolution mode were chosen to visualize the real-time R_{ON} evolution on the oscilloscope screen during a monitor window of 10 mins. The bottom contour of the waveforms during switching (from t = 0 s to t = 300 s in Fig. 6) depicts the evolution of R_{ON} while the DUT is switched on. A long voltage-dependent transient is observed before R_{ON} stabilizes (after which no substantial change in R_{ON} can be observed any longer), i.e., ~ 3 mins at $V_{ds(OFF)}$ = 100 V and ~ 10 s at $V_{ds(OFF)}$ = 400 V. It is also interesting to notice that after stopping switching and permanently turning on the DUT (after t = 300 s in Fig. 6), it still takes a long time for R_{ON} to recover back to the static R_{dc} value (which is also $V_{ds(OFF)}$ dependent). During the whole monitor window of 10 mins, the device temperature variance was small (< 4 °C) and therefore self-heating effect could be excluded, which is not possible with conventional inductive or resistive loaded circuits, e.g., Buck converters.

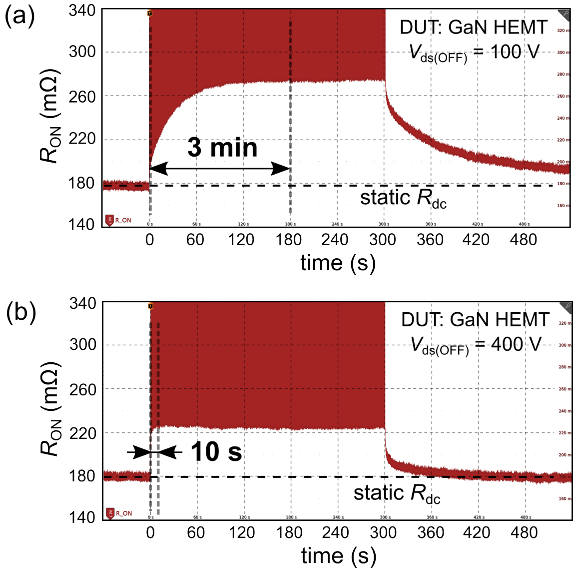

Fig. 6. Real-time monitoring of the dynamic R_{ON} before, during, and after switching at 10 kHz from t = 0 s for 5 mins at (a) $V_{ds(OFF)}$ = 100 V, and (b) $V_{ds(OFF)}$ = 400 V. Heating is not responsible for the transients before R_{ON} stabilizes as the temperature variance is small (< 4 °C) within the measurement window of 10 mins. Significant trapping and de-trapping time constants can be observed.

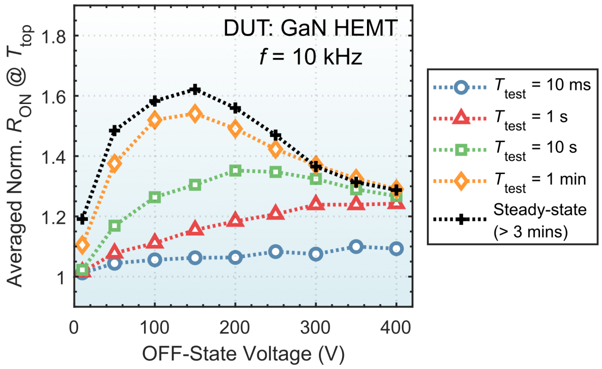

Fig. 7. Averaged normalized R_{ON} over the ON-time of the last pulse in multi-pulse tests at 10 kHz for a total test time ranging from 10 ms to 1 min, the number of pulses being from 100 to 6 × 10^5. Multi-pulse tests with an arbitrary test time are not able to accurately capture the dynamic R_{ON} behaviors at steady-state and may lead to wrong conclusions such that dynamic R_{ON} barely exists.

The slow transient responses in Fig. 6 suggest that results from multi-pulse tests (typically < 1 ms) are not representative of the dynamic R_{ON} behaviors at steady-state. To confirm this, we also performed multi-pulse tests for the same DUT at 10 kHz for a total test time ranging from 10 ms to 1 min, which is equivalent to a number of pulses from 100 to 6 × 10^5. Again, the self-heating effect is negligible thanks to the no-load operation at a low switching frequency. The averaged R_{ON} computed for the last pulse is shown in Fig. 7 and compared to steady-state results measured after operating for more than 3 mins. As can be seen, the time required for the dynamic R_{ON} to stabilize depends on $V_{ds(OFF)}$, with R_{ON} approaching the steady-state values more slowly for the lower voltage range ($V_{ds(OFF)}$ < 200 V) than for the higher voltage range. Although the number of pulses applied here is much larger than in

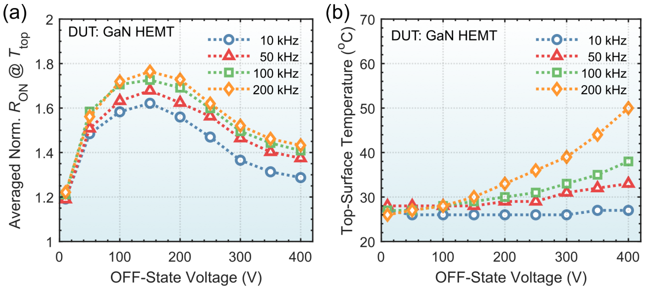

Fig. 8. (a) Averaged normalized R_{ON} of the GaN DUT over the ON-time at different switching frequencies and OFF-state voltages. (b) Top-surface temperature of the DUT measured under steady-state conditions.

typical multi-pulse tests, these results can still lead to spurious conclusions if the dynamic R_{ON} has not yet stabilized. For example, with a test time of 10 ms, one may conclude that dynamic R_{ON} barely exists, and with a test time of fewer than 1 s, one cannot capture the partial recovery pattern at high voltages (Fig. 7). This could explain the monotonic voltage dependence observed for GaN devices from the same manufacturer in [7] and [8], which only applied a few hundred pulses and performed measurements before the dynamic R_{ON} stabilized. Also, in Figs. 6 and 7, we did not apply any pre-stress time and the DUT was fully relaxed before tests to ensure consistent measurements and comparisons. This is not always practiced in pulsed measurements and could lead to conflicting results. Results in Figs. 6 and 7 clearly highlight the need for steady-state methods for accurate measurements of dynamic R_{ON}, and more importantly, raise awareness of these inconsistencies from pulsed measurements.

With a consistent measurement method, we also evaluated dynamic R_{ON} at higher switching frequencies at steady-state and studied its effect, which can be used to predict the device conduction losses in real-circuit applications. Fig. 8(a) shows the averaged R_{ON} values over the ON-time at different switching frequencies and $V_{ds(OFF)}$ along with the corresponding T_{top} in Fig. 8(b). An increase in R_{ON} with frequency is observed, which directly correlates to the relaxation pattern during the ON-time (Fig. 5(c)) and the reduced relaxation time at higher frequencies. More remarkably, the dynamic R_{ON} shows a non-monotonic dependence on $V_{ds(OFF)}$, which peaks at around 150 V with an increase of 60% – 80% and partially recovers to 30% – 40% at 400 V. This behavior concurs well with device physics models ascribing the recovery to an increased hole flow that can partially neutralize trapped electrons, by buffer leakage [11] and/or by enhanced impact ionization under high electric fields [3].

It should be noted that in this letter the dynamic R_{ON} of the GaN DUT was characterized only under hard-switching operations. However, the proposed measurement concept and the active measurement circuit are very general and could also be used in soft-switching applications, where GaN devices can be operated at higher switching frequencies and the effect of hot-electron trapping can be essentially excluded from OFF-state trapping.

The proposed method enabled the observation of slow and voltage-dependent transient response of dynamic R_{ON} in the tested type of GaN device, and can also be applied to test the stabilization time of dynamic R_{ON} for other devices. Other types of GaN devices may behave differently in terms of dynamic R_{ON} degradation, but this work raises awareness of the effect of poorly measured dynamic R_{ON}, as illustrated in Fig. 1 and in our multi-pulse tests (Fig. 7), and highlights that steady-state methods should be applied for accurate measurements to predict their performance in real power converter operations. Future works include a comprehensive comparison of different GaN technologies under different working conditions.

IV. CONCLUSION

In this letter, we proposed a new measurement method to evaluate the dynamic R_{ON} of GaN HEMTs while minimizing self-heating even at steady-state. The results show that a notable dynamic R_{ON} increase still exists (from 20% to 80% at different $V_{ds(OFF)}$) for the tested commercial GaN HEMT, along with large trapping time constants (1 – 100 s). These results underscore the need for steady-state measurements to accurately determine device conduction losses for converter designs and reveal that pulsed measurements with an arbitrary test time might fail to give an accurate picture of dynamic R_{ON} behaviors. With this in mind, the proposed method can be used to standardize the measurements of dynamic R_{ON} for benchmarking different GaN technologies and to predict their *in situ* ON-state performance at steady-state.

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