A new Method for Dynamic Ron Extraction of GaN Power HEMTs

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Abstract

Degradation of the dynamic on-state resistance $R_{ON}$ of GaN High-Electron-Mobility Transistors (HEMTs) is commonly observed under switching conditions with high drain current, high blocking voltage and high switching frequency. In order to determine this on-state resistance, specific measurement methods need to be developed. Since the drain source voltage of the device changes between hundreds of volts in the off-state and a few mill-volts in the on-state, an accurate determination of the on-state voltage $V_{DS_{ON}}$ is not achievable with standard measurement equipment due to the saturation of the DSO's input channel. In this paper, a voltage clamping circuit used to extract the dynamic on-state resistance $R_{ON}$ of GaN HEMTs is presented. This method is based on a high-voltage, fast-switching zero recovery SiC Schottky diode. The circuit allows an accurate measurement of $R_{ON}$ from 100 ns after turn-on to any arbitrary time and is feasible for operation at high switching frequencies up to 1MHz. Experimentally, the dynamic on-state resistance of 600V normally-off GaN HEMTs is investigated applying this method.

1. Introduction

The development of new power semiconductor devices is one of the main technical strategies to achieve higher efficiency in power conversion systems. Wide-bandgap power semiconductor devices based on Gallium Nitride (GaN) and Silicon Carbide (SiC) offer several advantages for power converters compared to the state-of-the-art Si power devices due to attractive material properties such as a high breakdown field, which make them suitable for several high-voltage applications [1]. However, electron trapping in GaN HEMTs causes current collapse and increase of the on-state resistance ($R_{ON}$) under dynamic conditions, representing a fundamental challenge for GaN researchers and developers. A low and stable dynamic on-state resistance $R_{ON}$ directly after the transient from off-state to on-state is crucial for realizing highly efficient power conversion systems, especially for high-voltage and high-frequency applications. In order to measure and display this on-state resistance, the measurement equipment must be able to capture and observe the on-state voltage $V_{DS_{ON}}$ directly after the transients in the nanoseconds range. Principally, the instantaneous dynamic value of $R_{ON}$ can be extracted from the measured $V_{DS_{ON}}$ divided by the measured drain current $I_D$ during on-state. However, since the device voltage changes between hundreds of volts in the off-state and a few mill-volts in the on-state, an accurate determination of $V_{DS_{ON}}$ is not achievable with standard measurement equipment. In the last years, few references ([1] - [3]) have discussed how to measure the dynamic on-state resistance of fast-switching power devices. Clamping measurement approaches have been demonstrated in [4] - [6].

In this work, we present a new feasible measurement method to study the dynamic on-state resistance. The method is applied to GaN transistors which are operated in buck- and boost converters, providing the main features of highly efficient DC-DC converters. Fig. 1 shows the hardware setup and the schematic test circuit including the proposed clamping circuit. The setup...
is configurable, in this case it is operated as a buck converter, with either high- or low-side power semiconductor switch. A 600V normally-off GaN HEMT [7] is investigated within this setup.

Fig. 1. Hardware test setup and circuit diagram including the proposed measurement clamping circuit.

2. State-of-the-art Voltage Clamping Circuit

A summary of published voltage clamping circuits used to measure the dynamic on-state voltage \( V_{\text{DS(on)}} \) is given in Fig. 2. The first clamping circuit in Fig. 2a consists of a Zener diode and a high ohmic resistor. The input terminals are connected directly to the drain and source of the investigated transistor, and the output voltage is equal to the rated Zener diode voltage \( V_z \) during the off-state and to the DUT’s \( V_{\text{DS(on)}} \) during the on-state. The advantage of this circuit is its simplicity, no external voltage source and no differential measurement are needed. The long time reaction (RC-delay) of \( V_{\text{DS(on)}} \) caused by the resistor \( R \) in series with the Zener diode capacitance is the main disadvantage of this method. In circuit II [4], the RC-delay is significantly reduced by using a p-channel MOSFET (RC-delay < 300ns).

Circuit III [5] is a combination of circuits I and II, and possesses the advantages of both methods. The clamping circuit shown in Fig. 2d represents the state-of-the-art [6]. Compared to the conventional clamping circuits, this method allows a higher measurement accuracy due to the use of an extremely fast-switching diode with very small parasitic capacitance (\( C_{\text{Parasitic}} \approx 2 \) pF) and the employment of the current mirror technique. On the other hand, this approach requires the use of a differential probe. The input amplifier of the differential probe cannot completely reject the common mode signal during the measurement. Consequently, a small amount of the common-mode voltage will appear in the output and add an additional erroneous value to the measured signal [8]. Nevertheless, this method ensures a high measurement accuracy of \( R_{\text{ON}} \) and a small RC-delay compared to the conventional circuits.
In the next section, an alternative clamping circuit is proposed which is based on a high-voltage zero recovery SiC Schottky diode (600V/1A). The features of all described clamping circuits are summarized in table 1.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Circuit II</th>
<th>Circuit III</th>
<th>Circuit IV</th>
<th>Circuit V (proposed)</th>
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<td>MOSFET</td>
<td>MOSFET</td>
<td>p-n Diode</td>
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<td>&lt; 300 ns</td>
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<td>( \downarrow ) GND</td>
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<td>Subtracted</td>
<td>Subtracted</td>
<td>Not introduced</td>
</tr>
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</table>

Table 1. Comparison between the voltage clamping circuits

### 3. Proposed SBD-based Clamping Circuit

Fig. 3 shows the schematic of the test circuit (buck converter) during turn-on and turn-off of the DUT. The proposed voltage clamping method is based on a quite simple circuit with the SiC Schottky diodes D1 and D2 (CSD01060) representing the main components. As depicted in Fig. 3a, during the off-state the GaN HEMT will turn off and a charging current will flow through the SiC Schottky diode D1 and charge the 450uF capacitor C. The voltage drop across the capacitor C is clamped to the rated voltage \( V_Z \) of the Zener diodes D3 and D4 and used during the on-state to supply the rest of the circuit.

When the DUT is switched on (Fig. 3b), the capacitor C starts to discharge, and the discharging current will flow through the GaN HEMT via D2. As a result, the measured voltage drop \( V_{\text{DSON}*} \) at the D2-anode terminal represents the actual on-state voltage \( V_{\text{DSON}} \) of the GaN HEMT plus the forward voltage \( V_F \) of the Schottky diode D2. The measured value needs to be corrected by this voltage offset to get the actual \( V_{\text{DSON}} \). Since the selected series resistor \( R_{\text{DRIVE}} \) is 100\( \Omega \), the forward current \( I_F \) through D2 will reach a few milliamps. Hence, the measured forward voltage \( V_F \) of D2 is kept nearly unchanged, with a very low tolerance between 830 mV and 840 mV due to the small
change of the diode forward current $I_F$. Fig. 4 depicts the measured forward characteristics of the SiC Schottky diode at 25°C and 75°C case temperature. Since the maximum forward current in $D_2$ will not be higher than 30 mA in any case, an increase of the junction temperature during the measurement is not expected. The provided current $I_{DRIVE}$ is adjusted by the selected Zener voltage $V_Z$ and the resistor $R_{DRIVE}$.

![SiC Schottky Diode (CSD01060)](image)

Fig. 4. Measured forward characteristics of the SiC Schottky diode (CSD01060) at 25°C and 75°C.

The measured on-state voltages $V_{DSON}$ of the investigated GaN transistor with and without the proposed clamping circuit are compared in Fig. 5. All measurements were performed using a LeCroy 400 MHz Oscilloscope, a CP015 LeCroy 500 MHz Voltage Probe, and a 250 MHz Pearson Current Sensor (Model 2877). It can be seen that after the decay of transient effects, an accurate value for $V_{DSON}$ is obtained using the clamping circuit. The peaks on the clamped voltage $V_{DSON}$ are caused by the parasitic capacitance of diode $D_2$. Therefore, the capacitance is minimized by using a small SiC Schottky diode.

![Fig.5. Measured waveforms of the investigated normally-off GaN HEMT with and without clamping circuit. $V_{DS} = 150$ V and $I_D = 6$ A, switching frequency 400 kHz, $T=25^\circ$C.](image)

Fig. 5. Measured waveforms of the investigated normally-off GaN HEMT with and without clamping circuit. $V_{DS} = 150$ V and $I_D = 6$ A, switching frequency 400 kHz, $T=25^\circ$C.

Fig. 6a depicts exemplary measured waveforms of the investigated normally-off GaN HEMT during turn-on in the double pulse test. The off-state voltage $V_{DS}$ is 200 V, and the switched drain current is 5 A at an ambient temperature of 25°C. The evaluated $R_{ON}$ in Fig. 6b is measured for different off-state voltages, varying from 50 V to 200 V at a constant drain current $I_D = 5$ A. As stated previously, an important issue in this method is to keep the forward current of the Diode $D_2$ as small as possible to prevent any increase of the diode temperature.

The dynamic on-state resistance is related to the off-state voltage and the switched current. In Fig. 7a, drain currents are varied from 3 A to 7 A at a constant drain source voltage $V_{DS} = 200$ V, and in Fig. 7b, the drain source voltage $V_{DS}$ is varied from 50 V to 200 V with a constant drain current $I_D$ of 5 A. In each figure, the stress point, i.e. the time which has passed since the occurrence of the switching event is included as a further parameter. The results show that
switching from a high blocking voltage (V_DS) as well as switching higher drain currents significantly contribute to the increase of the dynamic R_ON, suggesting that this increase is due to a current collapse in GaN HEMTs.

Fig. 6. (a) Measured transients including V_DSON using the proposed clamping circuit at V_DS = 200V and drain current I_D = 5 A. (b) Measured dynamic R_DSON directly after the switching at different drain source voltages V_DS varying from 50V to 200V and 5A drain current I_D. The test is carried out using the double pulse circuit at 25°C.

Fig. 7. Measured dynamic on-state resistance R_DSON for (a) different drain currents I_D varying from 3A to 7A with constant drain source voltage V_DS = 200V and (b) different drain source voltage V_DS varying from 50V to 200V with a constant drain current I_D of 5A. The test is carried out using the double pulse circuit at 25°C.

4. Conclusions

In this work, a clamping circuit for the dynamic R_ON measurement of GaN HEMTs is presented. The circuit allows an accurate measurement of R_ON from 100ns after turn-on to any arbitrary time at high switching frequencies up to 1MHz. Different to the state-of-the-art, the proposed circuit has the advantage that no differential voltage probe is required to measure the on-state voltage and no external supply voltage is needed. Moreover, a blocking voltage up to 600V can be clamped due to the use of a high voltage SiC Schottky diode. However, the proposed circuit introduces a voltage offset to the measured V_DSON value which has to be compensated. The achieved measurement results show that high off-state voltages (V_DS) and high drain currents are major contributions to the increase of the dynamic R_ON in GaN HEMTs. This is still a challenge for GaN technology, and a focus of current device research and development.
5. Acknowledgement

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6. References


