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Impact of high-power stress on dynamic ON-resistance of high-voltage GaN HEMTs

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Abstract- We have investigated the impact of high-power (HP) stress on the dynamic ON-resistance ($R_{ON}$) in high-voltage GaN High-Electron-Mobility Transistors (HEMT). We use a newly proposed dynamic $R_{ON}$ measurement methodology which allows us to observe $R_{ON}$ transients after an OFF-to-ON switching event from 200 ns up to any arbitrary length of time over many decades. We find that HP-stress results in much worsened dynamic $R_{ON}$ especially in the sub-ms range with minor changes on a longer time scale. We attribute this to the stress-induced generation of traps with relatively short time constants. These findings suggest that accumulated device operation that reaches out to the HP state under RF power or hard-switching conditions can result in undesirable degradation of dynamic $R_{ON}$ on a short time scale.

I. INTRODUCTION

In the last decade, GaN Field-Effect Transistors have emerged as a promising disruptive technology for both power electronics and high power microwave applications. However, in spite of great progress in device fabrication and material growth technologies, limited device reliability still precludes the wide spread deployment of this technology [1].

A particular concern is the dynamic ON-resistance ($R_{ON}$) in which after an OFF-ON switching event, $R_{ON}$ of the transistor remains high for a certain period of time [2]. This is also known as current collapse and greatly affects the power electronics and RF power applications of these devices [3]. The detailed physics of dynamic $R_{ON}$ are not completely understood. Much less understanding exists regarding the impact of electrical stress on dynamic $R_{ON}$ [2, 4].

We have recently developed a new measurement technique that allows the observation of $R_{ON}$ transients over a time period that spans many decades [5]. Using this technique, we study here the impact of high-power (HP) stress on dynamic $R_{ON}$. We find that HP-stress results in much worsened dynamic $R_{ON}$ in the sub-ms range. This occurs as a result of the creation of traps with relatively short time constants. On a longer time scale, negligible degradation of dynamic $R_{ON}$ is observed. Our results point out the importance of characterizing electrically stress-induced dynamic $R_{ON}$ and current collapse over very short time scales.

II. EXPERIMENTS

In this study, we have characterized industrial research AlGaN/GaN HEMTs grown on SiC by MOCVD. The device features an integrated field plate and a source-connected field plate and exhibits a breakdown voltage higher than 200 V.

We have stressed these devices in the high-power state with $V_{GS}=2$ V ($I_{D} \approx 0.6$ A/mm) and $V_{DS}=20$ V at room temperature. The channel temperature during the stress is estimated to be around 380 C. This is a very harsh stress condition designed to accelerate the rate of degradation. We interrupt the stress every minute and characterize the evolution of important figures of merits such as $R_{ON}$ and maximum drain current ($I_{DMAX}$) using a benign characterization suite. Dynamic $R_{ON}$ is investigated using a recently proposed methodology [5] in which $R_{ON}$ recovery transients originating from an OFF-to-ON switching event are recorded from 200 ns to any arbitrary length of time. This is accomplished by combining

![Fig. 1](https://example.com/figure1.png)

**Fig. 1** Time evolution of $R_{ON}$ and $I_{DMAX}$ (normalized to their initial values) during a constant HP-state stress in GaN HEMTs. The stress conditions are $V_{GS}=2$ V, and $V_{DS}=20$ V. Up to about 30 min of stress, the device characteristics show minor changes. Beyond 30 min, prominent degradation in both $R_{ON}$ and $I_{DMAX}$ is observed.
measurements using an Auriga AU4750 pulsed IV system and an Agilent B1500A semiconductor device analyzer. We applied this method to five identical test systems and an Agilent B1500A semiconductor device measurements using an Auriga AU4750 pulsed IV system and an Agilent B1500A semiconductor device analyzer. We applied this method to five identical test devices fabricated on the same chip after HP-stress analyzer. We applied this method to five identical test devices fabricated on the same chip after HP-stress analyzer. We applied this method to five identical test devices fabricated on the same chip after HP-stress analyzer. We applied this method to five identical test devices fabricated on the same chip after HP-stress analyzer. We applied this method to five identical test devices fabricated on the same chip after HP-stress analyzer.

Fig. 1 plots the time evolution of DC $R_{ON}$ and $I_{D_MAX}$ normalized to their initial values as a function of stress time for the sample that was stressed for 40 min. The device shows quite robust characteristics up to 30 min, but beyond this point, significant degradation takes place. The samples stressed for 10, 20 and 30 mins exhibit very minor degradation in their DC $R_{ON}$ and $I_{D_MAX}$ values, consistent with the results of Fig. 1.

Fig. 2 shows $R_{ON}$ recovery transients from 200 ns up to 200 s for all devices after an OFF-state pulse switching in different samples that have been subject to different HP-state stress periods ranging from 0 to 40 min. Up to 30 min of stress, minor changes in dynamic $R_{ON}$ are observed. After 40 min of stress, there is a more than ten-fold increase in dynamic $R_{ON}$. Very fast $R_{ON}$ recovery down to ms range is observed in all cases.

In addition, $R_{ON\_DC}/R_{ON\_DC\_virgin}$ shows a small increase up to 16% in comparison to dynamic $R_{ON}$ suggesting minor permanent (non-transient) degradation. After 40 min of stress, there is a prominent increase of the magnitude of transients with short time constants.

Dynamic $R_{ON}$ measurements at different temperatures (T) have been performed with the goal of selecting an appropriate time scale for the study of degradation. These findings highlight the importance of dynamic $R_{ON}$ and current collapse in GaN HEMTs after electrical stress.

In order to understand the physical origin of these prominent transients, we have analyzed the time domain $R_{ON}$ data by fitting it with a sum of exponentials [6]. The amplitude of the various components as a function of their respective time constants is shown in Fig. 4. It is clear that after 40 minutes of stress time, fast transients emerge with time constants in the μs to ms range. In contrast, negligible changes occur in the long time constant domain.

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Fig. 1: Time-domain stress time in a semilog scale. Dynamic $R_{ON}$ mostly increases in a time range from 200 ns up to a few ms. $R_{ON\_DC}/R_{ON\_DC\_virgin}$ shows small increase up to 16% in comparison to dynamic $R_{ON}$ suggesting minor permanent (non-transient) degradation.

Fig. 2: Dynamic $R_{ON}$ transients from 200 ns up to 200 s from OFF ($V_{GSO}$= -10 V, $V_{DSO}$= 50 V) to ON ($V_{GS}$= 1 V and $V_{DS}$= 0.05–0.5 V) switching in different samples that have been subject to different HP-state stress periods ranging from 0 to 40 min. Up to 30 min of stress, minor changes in dynamic $R_{ON}$ are observed. After 40 min of stress, there is a more than ten-fold increase in dynamic $R_{ON}$. Very fast $R_{ON}$ recovery down to ms range is observed in all cases.

Fig. 3: Dynamic $R_{ON}$ ($R_{ON}/R_{ON\_DC}$) of Fig. 2 at different times (200 ns, 10 μs, and 10 ms) and $R_{ON\_DC}/R_{ON\_DC\_virgin}$ ($R_{ON\_DC}$ value in the virgin device) as a function of HP-state stress time in a semilog scale. Dynamic $R_{ON}$ mostly increases in a time range from 200 ns up to a few ms. $R_{ON\_DC}/R_{ON\_DC\_virgin}$ shows small increase up to 16% in comparison to dynamic $R_{ON}$ suggesting minor permanent (non-transient) degradation.

Fig. 4: Time-constant spectra for $R_{ON}$ transients of Fig. 2. A sum of exponential terms with time constant ranging from $10^{-7}$ s to $10^3$ s is used to fit the measurement data. The appropriate equation for fitting is indicated in the inset. After 40 min of stress, there is a prominent increase of the magnitude of transients with short time constants.

with $V_{GSO}$= -10 V and $V_{DSO}$= 50 V. $R_{ON}$ is continuously being measured at $V_{GS}$= 1 V and $V_{DS}$= 0.05–0.5 V with a duty cycle of 10%. In a virgin device, after this switching event, $R_{ON}$ at 200 ns is about 36% higher than in DC ($R_{ON\_DC}$) and recovers back within ~10 ms. After HP stress, dynamic $R_{ON}$ at 200 ns increases but the recovery takes place on a similar time scale. After 40 min of stress time, the dynamic $R_{ON}$ at 200 ns dramatically increases more than tenfold over $R_{ON\_DC}$- This is very problematic for both power switching and RF applications.

Fig. 3 shows dynamic $R_{ON}$ ($R_{ON}/R_{ON\_DC}$) at 200 ns, 10 μs and 10 ms as well as $R_{ON\_DC}/R_{ON\_DC\_virgin}$ ($R_{ON\_DC}$ value in the virgin device) as a function of stress time in a semilog scale. This graph leaves clear how dynamic $R_{ON}$ increases greatly between 30 and 40 min of stress but only on a time scale in the ms range. Beyond 10 ms or so, few changes are observed. In addition, $R_{ON\_DC}/R_{ON\_DC\_virgin}$ shows a small increase up to 16% in comparison to dynamic $R_{ON}$ suggesting minor permanent (non-transient) degradation. These findings highlight the importance of selecting an appropriate time scale for the study of dynamic $R_{ON}$ and current collapse in GaN HEMTs after electrical stress.

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Dynamic $R_{ON}$ measurements at different temperatures (T) have been performed with the goal of selecting an appropriate time scale for the study of degradation. These findings highlight the importance of dynamic $R_{ON}$ and current collapse in GaN HEMTs after electrical stress.
of illuminating the physical origin of these transients. \textbf{Fig. 5} shows $R_{ON}$ transients at $T$ between 25 C and 150 C for the sample that has been subject to 40 min HP-stress. The recovery transient is considerably accelerated as $T$ increases. The evolution of the dominant time constants with $T$ is depicted in an Arrhenius plot in \textbf{Fig. 6}. A thermally activated behavior for the time constants is obtained that suggests that conventional traps (as opposed to traps that communicate with the channel through a tunneling process [5,9,10]) are responsible for the increase in dynamic $R_{ON}$. \textbf{Fig. 6} reveals that the dominant trap energy levels that have been created have ionization energies of 0.31, 0.45, 0.53 and 0.57 eV. Traps with low energy levels such as 0.23, 0.31, 0.45 eV appear to have been generated as a result of the HP-stress whereas deeper traps already existed in the virgin sample but their density seems to have increased [5]. The observed traps are presumed located below the conduction band edge of the AlGaN barrier inside its body or at the surface. Similar trap energy levels have also been reported in similar structures after electrical stress by other authors [7-8].

III. CONCLUSIONS

In summary, we have experimentally observed a large increase in dynamic $R_{ON}$ on a short-time scale after high-power electrical stress of GaN HEMTs. The cause is attributed to the formation of shallow traps inside the AlGaN barrier or at its surface. This work suggests that prolonged device operation of GaN HEMTs under RF power conditions (in microwave applications) or under hard-switching conditions (in power management) can result in an undesirable increase of dynamic $R_{ON}$ on a very short time scale.

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REFERENCES


