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

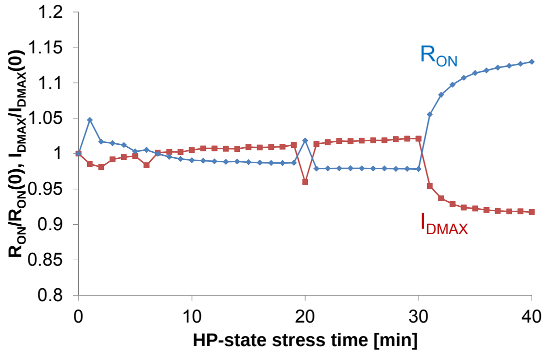

Fig. 1 Time evolution of R_{ON} and I_{DMAX} (normalized to their initial values) during a constant HP-state stress in GaN HEMTs. The stress conditions are V_{GS}= 2 V, and V_{DS}= 20 V. Up to about 30 min of stress, the device characteristics show minor changes. Beyond 30 min, prominent degradation in both R_{ON} and I_{DMAX} is observed.

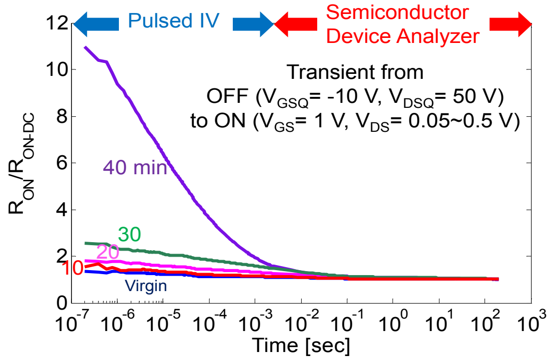

Fig. 2 Dynamic R_{ON} transients from 200 ns up to 200 s from OFF (V_{GSQ}= -10 V, V_{DSQ}= 50 V) to ON (V_{GS}= 1 V and V_{DS}= 0.05~0.5 V) switching in different samples that have been subject to different HP-state stress periods ranging from 0 to 40 min. Up to 30 min of stress, minor changes in dynamic 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.

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 times of 0, 10, 20, 30 and 40 mins.

Fig. 1 plots the time evolution of DC R_{ON} and I_{DMAX} 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_{DMAX} 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 with V_{GSQ}= -10 V and V_{DSQ}= 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.

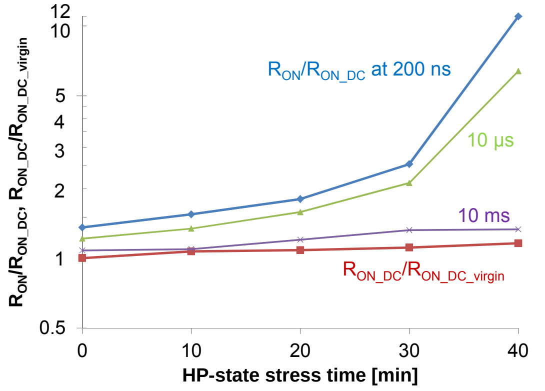

Fig. 3 Dynamic R_{ON} (R_{ON}/R_{ON_DC}) of **Fig. 2** at different times (200 ns, 10 µs, and 10 ms) and $R_{ON\_DC}/R_{ON\_DC\_virgin}$ (R_{ON_DC} value in the virgin device) as a function of HP-state stress time in a semilog scale. Dynamic R_{ON} mostly increases in a time range from 200 ns up to a 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.

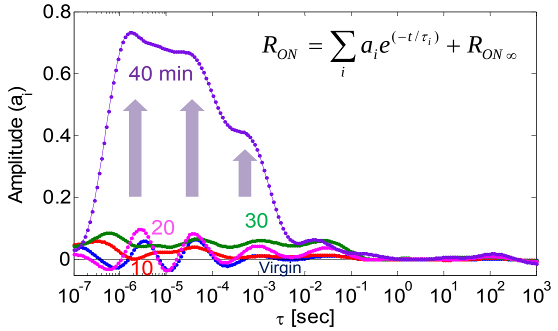

Fig. 4 Time-constant spectra for R_{ON} transients of **Fig. 2**. A sum of exponential terms with time constant ranging from 10^{-7}s to 10^{3}s is used to fit the measurement data. The appropriate equation for fitting is indicated in the inset. After 40 min of stress, there is a prominent increase of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

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 µs 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.

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.

Dynamic R_{ON} measurements at different temperatures (T) have been performed with the goal

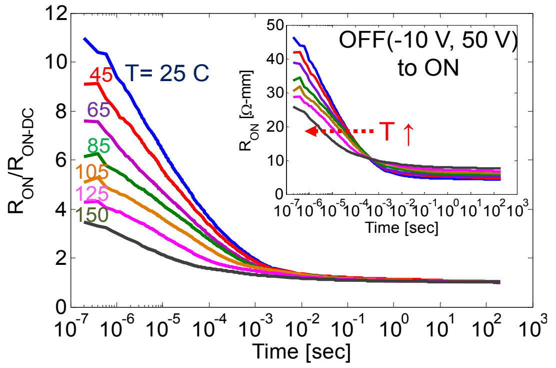

Fig. 5 R_{ON}/R_{ON_DC} transients at different temperatures between 25 C and 150 C for V_{GSQ}= -10 V and V_{DSQ}= 50 V after 40 min HP stress. The inset shows the absolute value of the R_{ON} transient. As the temperature goes up, the dominant transients are substantially accelerated. This suggests that the transients are due to generated traps.

of illuminating the physical origin of these transients. **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 **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}. **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].

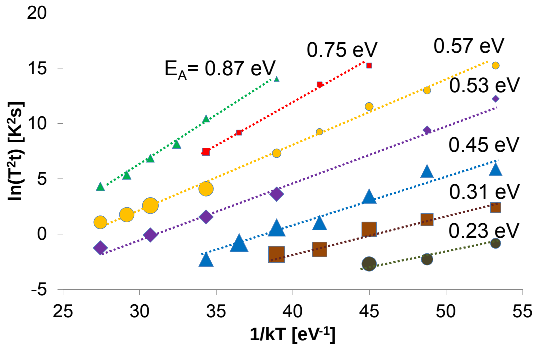

Fig. 6 Arrhenius plot of time constant spectra extracted from **Fig. 5**. The size of the symbols is proportional to the height of the time constant peaks. The dominant trap energy levels are located at 0.31, 0.45, 0.53 and 0.57 eV below the conduction band edge of the AlGaN barrier. These are the traps that are responsible for the dramatic increase in dynamic R_{ON} that is observed in a short time scale.

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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