Development of Transient Measurement Techniques for GaN RF On-Wafer Transistors

Simone Cangini, *Student Member, IEEE,* Alberto Santarelli, *Member, IEEE,*

***Abstract*—This project focuses on the characterization and modeling of dynamic effects in novel GaN-on-Si HEMT devices. To this aim, a tailored experimental set-up is developed to enable measurements in transient or pulsed regimes, either in a stand-alone configuration, that could be combined with pulsed/transient S-parameter measurements. Starting from the procedures typically adopted for GaN-on-SiC devices, new characterization procedures tailored to study the dispersive behavior peculiar to GaN-on-Si are developed. These techniques will allow to identify the involved time-constants, as well as to extract suitable modeling dataset accounting for low-frequency dispersion.**

***Keywords*—GaN, charge trapping, on-wafer measurements.**

I. INTRODUCTION

Gallium Nitride (GaN) High-Electron-Mobility Transistor (HEMT) technology is receiving more and more importance in radio-frequency (RF) applications due to its high-power capabilities and high operational bandwidths.

Despite its excellent properties, both GaN-on-SiC and GaN-on-Si are known to display particular microelectronic mechanisms inducing low-frequency dispersion phenomena. While improvement in semiconductor manufacturing always tends to minimize such effects, commercial transistor devices and Microwave Monolithic Integrated Circuit (MMIC) processes are still affected, at present, by various non-idealities. This impairs the full exploitation of GaN especially in those contexts where high linearity is a hard constraint.

Among these non-idealities, it has been reported a specific decrease in the drain supply current for increasing RF output powers, referred to as *current collapse*, which correspondingly causes a reduction in the RF output power levels. Also, GaN-based amplifiers display a so-called *soft compression* of the RF gain, which creates a number of issues in the design of linear PAs and their linearization by digital predistortion (DPD). Another experimental element hinting at the presence of spurious nonlinear dynamics is the difference between the dynamic gain profiles observed when the PAs are excited with modulated signals, in comparison with the static curves measured using Continuous-Wave (CW) RF excitation.

The objective of this project is to develop measurement functionalities and characterization methods for assessing the global large-signal behavior of low-frequency dispersive effects in GaN HEMTs. The idea is to develop a black-box approach based only on experimental data, without any a-priori physics-based assumption. The studied methods exploit the wideband behavior and flexibility of operation of a newly developed setup in order to devise an accurate transient testing procedure.

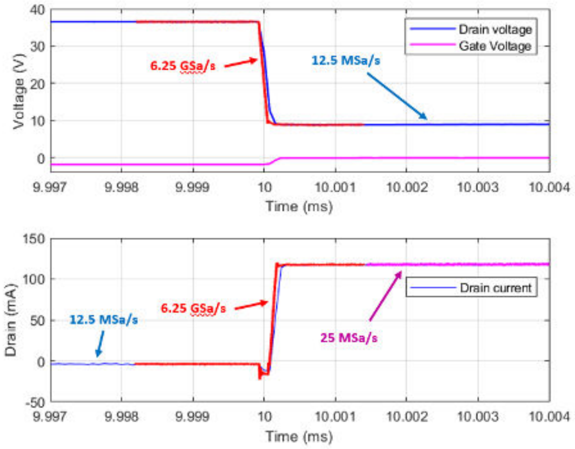

Fig. 1. Multiple time-scale acquisition.

II. MULTIPLE TIME-SCALE ACQUISITION

Some characterization techniques involve pulsed voltage excitations for both gate and drain. These pulsed waveform needs to be as much ideal as possible for the modeling to be accurate, namely the pulse edge should be as short as possible e.g., in the ns-range. At the same time, the pulse period needs to be large to allow charge recovery.

These two requirements are challenging from a measurement point of view, given that long acquisition times (in the order of seconds) in practice imply low sampling rate due to the limited instrument memory available. The target is the acquisition at the highest sampling rate available (for the oscilloscope in use, that would correspond to 6.25 GSa/s) at least for both rising and falling edge for capturing also fast transients in drain current.

Moreover, as the project aims at a global understanding of the dynamics behavior due to trapping, a very large number of pulse configurations with different initial and final voltage levels will be needed in order to span the whole V_{GS} - V_{DS} plane resulting in a very large dataset.

To address the problem, a multiple time-scale acquisition technique, has been adopted. The solution developed in this thesis is based on a flexible segmentation of the waveform to be acquired, where the time segments can be disjointed in time, hence using periodic triggering as a reference for

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Simone Cangini was M.Sc. student and is now Ph.D. student at the University of Bologna, 40126 Bologna, Italy.

Alberto Santarelli is Professor at the Dept. Electrical, Electronic, and Information Engineering, University of Bologna, 40126 Bologna, Italy.

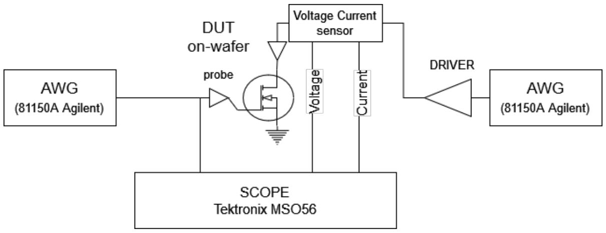

Fig. 2. Proposed setup used for acquisition.

stitching the multiple segments acquired through different acquisitions. Multiple segments at different sampling rate are acquired for pulsed waveforms with 50% duty cycle, especially deploying high time resolution on the transition front, where spurious glitches or ringing might get mixed up short-time dynamics, then extending the measure large periods adapting the sampling rate.

As visible in Fig. 2, for voltage and current measurement we employed a broadband voltage and current sensor, based on shunt resistor for the current reading. This sensor aims to reduce the impact of the sensing instrumentation in between the driver output and the DUT on-wafer probes, lowering physical length between the two and maintaining 50Ω coupling. Sensor has been calibrated from DC to $100MHz$; a SOLT calibration has been fulfilled and optimized for the pulse response. The driver adopted is ADA4870, capable to output 1A at max 40V of full voltage swing. Band limitations involving the driver adopted has been overcome by means of pre-emphasis techniques that allowed to obtain sharp edges with low residual ripple for edge timing as low as 20ns.

III. TRAP ACTIVATION ENERGY IDENTIFICATION

Among the various configurations and transient behaviors performed in the measurement campaign, the most prominent one is realized when the gate voltage changes from quasi pinch-off towards the 0 V, so that the HEMT channel is switched to a complete ON state while, concurrently, the drain voltage is switched from the maximum available value with the adopted drain driver ($\sim$ 38 V) to $\sim$ 10 V, which corresponds to the knee voltage of the device.

The described one is the configuration where both gate-related and drain-related lag effects contribute to the transient. The fact that the slowest and most evident transient is measured in these conditions is in accordance with theory [3].

The acquisition of such a transient configuration, corresponding to the $(V_{GS} = -1.8, V_{DS} = 38)_1$ V $\rightarrow$ $(V_{GS} = 0, V_{DS} = 10)_2$ V voltage step excitation, was then used as a fundamental one to identify relevant de-trapping time constants. Then, the identification of characteristic time constants should allow to identify the dominant trapping energy levels. Beyond their physical significance, these constants give an estimate of the device memory time scale, which is key behavioral information for developing accurate models Fig. 3.

Arrhenius plots obtained from thermally induced de-trapping current transients at different baseplate temperature are typically used to extract the trap activation energy (E_a). The Arrhenius plot for this DUT, extracted across the full measured temperature range and compensated for self-heating (thermal resistance $R_{th} = 56$ K/W mm as from foundry information) is shown in Fig. 4, confirming the presence of a single significant trapping process.

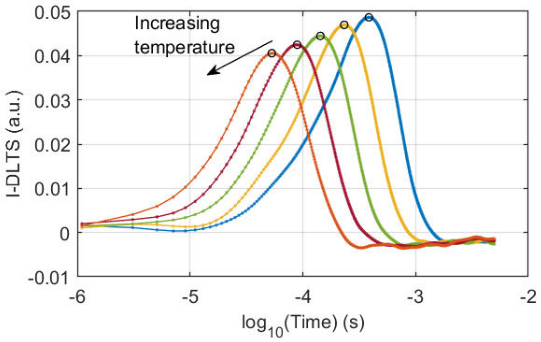

Fig. 3. Time constant spectra and thermal activation of the trap process, extracted from the drain current transient measurements.

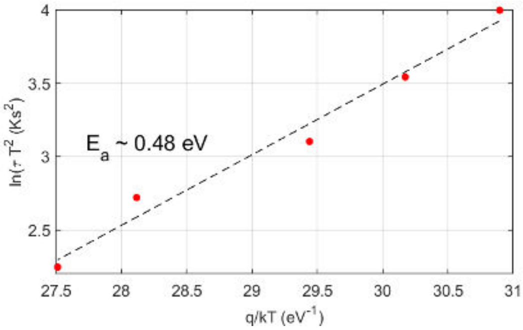

Fig. 4. Arrhenius plot extracted using the I-DTLS technique.

By comparing the measured energy level $E_a \simeq 0.48$ eV with the mechanisms studied in literature, one can derive the possible presence of impurities in nitrogen substitutional position, or the influence of Fe dopant. The results obtained here are fairly well aligned with the literature on this type of devices.

IV. IMPACT STATEMENT AND CAREER PLANS

The MTT-S scholarship has given me the opportunity to discover the RF and microwave fields from a very practical and interesting way. This chance triggered my curiosity and motivated me to undertake a Ph.D. program at the University of Bologna. I am looking forward to attending a future MTT-S conference as allowed by the provided scholarship.

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