Nonlinear Modeling of GaN HEMTs for RF and Microwave Applications

João L. Gomes, Luís C. Nunes, *Member, IEEE* and José C. Pedro, *Fellow, IEEE*

Abstract— **This report summarizes the main outcomes obtained during the 2020 MTT-S Graduate Fellowship after the award recognition. In total, three conference papers were published, describing a deeper understanding and two novel characterization techniques of the mechanisms governing AlGaN/GaN HEMT trapping effects. One of these papers was considered the 2nd best student paper. An additional journal paper resulted from the gathered knowledge, where a new analog circuit to compensate the self-biasing effects in GaN-based PAs is proposed.**

I. INTRODUCTION

INTEREST in GaN-based HEMTs has been on the rise in recent years, mainly because of its outstanding efficiency performance in RF power amplification and power conversion technologies. However, despite the high-power capabilities, high operating bandwidths and high-efficiency figures achieved by these devices, the presence of deep-level traps is still an impediment to highly linearized RF power amplifiers (PAs) and reliable power switches. Understanding these effects and their mechanisms contributes to their possible mitigation at the device manufacturing stage or improving the available compact models for RF applications, including PA design and compensation techniques. In this context, a great effort has been undertaken to thoroughly characterize the traps in GaN HEMTs responsible for the challenging slow-memory effects.

II. EXPLAINING THE DIFFERENT TIME CONSTANTS EXTRACTED FROM LOW-FREQUENCY Y_{22} AND I_{DS}-DLTS ON GAN HEMTS

For long, the scientific community was convinced that the capture time constant was too small to be properly quantified with modern pulsed measurement systems. The existence of slow memory effects in GaN HEMTs was thus commonly associated to the slow emission process. In fact, the idea that one can extract an emission time constant directly from Y_{22} measurements stems from the assumption that the capture process dynamics are too fast to be observable under low frequencies of excitation. The focus was then directed to accurately characterize the emission dynamics.

Nowadays, measuring the emission time constant in commercial GaN HEMTs is typically done by low-frequency Y_{22} or IDS-Deep-Level Transient Spectroscopy (DLTS). However, the reported values for these two methods display a large disparity between them, with Y_{22} yielding a much lower emission time constant. Given the importance of the emission time constant to both identify the trap's nature, as well as to achieve more accurate GaN HEMTs models, a clear interpretation of the Y_{22} and IDS-DLTS results was strongly needed.

In [1], we showed that the trapping time constant, not being a physical identity but a model parameter, can vary according to the extraction conditions. This dependence is clearly seen in Y_{22} and IDS-DLTS measurements, as they are made under small-signal steady-state and large-signal transient conditions, respectively. A theoretical explanation supported by the Shockley-Read-Hall (SRH) model was proposed, illustrating how time-constants extracted from IDS-DLTS, i.e., under charge carrier emission, must be longer than the ones obtained from Y_{22}, i.e., under equilibrium, and thus, where both emission and much faster capture processes play a role.

Therefore, the assumption often found in the literature that the capture process cannot manifest itself at low frequencies (where Y_{22} exhibits its maximum dispersion), being only a cause of the emission process, does not hold, as we have demonstrated with this work. Furthermore, although both methods could provide information about the emission time constant, it was the I_{DS}-DLTS that was shown to give a detrapping rate closely related to the trap's emission time constant. This finding may prove useful for future research dedicated to extracting the trap's fingerprints.

III. TRANSIENT PULSED S-PARAMETERS FOR TRAPPING CHARACTERIZATION

Dedicated pulsed I-V measurement techniques, like IDS-DLTS, have been widely adopted to study trapping effects. Despite the many variants to this method, the basic idea consists of setting the trapping state with some carefully chosen bias pre-pulse and then measure its influence on the drain current – commonly denominated as current collapse. Despite the recognized usefulness of this method, it is limited to probe the trapping mechanisms based solely on their influence upon the I_{DS} current. Nevertheless, it is at least plausible that trapping may also have a substantial impact on the transistor's intrinsic capacitances. So, without considering these dependencies could lead to significant inaccuracies on the equivalent-circuit model predictions.

This work was supported by the Portuguese Science and Technology Foundation, FCT (Ref. SFRH/BD/135839/2018).

The authors are with DETI, Instituto de Telecomunicações, Universidade de Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal (e-mails: joaolucas@ua.pt, cotimos@ua.pt and jcpedro@ua.pt).

In [2], we proposed an adaption to the standard pulsed S-parameter measurements. Contrary to previous approaches, our method describes the trapping dynamics acting on the various equivalent circuit model elements at guaranteed isothermal conditions. The proposed transient pulsed S-parameter measurement technique can be used to extract the trapping dynamics from G_m and G_{ds}, which is another way to sense the channel's current, and from the device's intrinsic capacitances. Therefore, this can be a valuable contribution to the actual understanding of the trapping mechanism. Fig. 1 illustrates one of the obtained results: the recovery transient of both G_{ds} and C_{gs} for a commercial GaN HEMT.

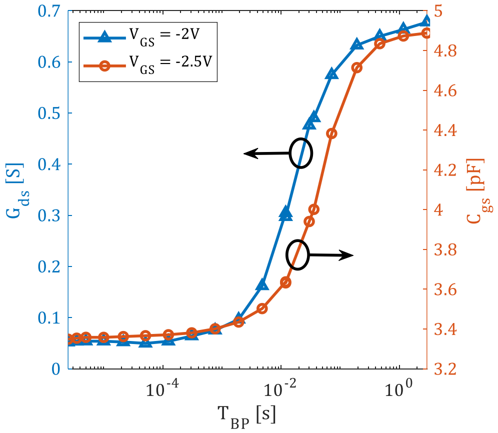

Fig. 1 C_{gs} and G_{ds} profiles obtained from transient pulsed S-parameters for $(V_{DSQ}, V_{GSQ}) = (60V, -9V)$ and $V_{DS} = 0V$.

IV. A TRANSIENT TWO-TONE RF METHOD FOR THE CHARACTERIZATION OF ELECTRON TRAPPING CAPTURE AND EMISSION DYNAMICS IN GAN HEMTS

In [3] we proposed a method for characterizing the trapping-related capture and emission time constants based on the transient inspection of the dynamic self-biasing of GaN HEMT-based PAs. As a method that utilizes two-tone RF excitations, it does not require specialized and expensive pulsing equipment. It can instead be performed using a conventional vector signal generator and a vector signal analyzer on a fully assembled PA. Moreover, the proposed method provides comprehensive measured data on the dynamics of charge trapping closer to the target operation conditions of the PA under test, when compared with the conventional pulsed I-V characterization.

As an extension to this work, in [4] we propose a behavioral model that approximates the SRH model with a piecewise-defined state-variable capture time constant and implement it as a fully analog electronic circuit, acting on the v_{GS} voltage, for the compensation of the dynamic self-biasing behavior of a GaN HEMT-based PA. It is shown that we can accurately preserve the class of operation of the PA and eliminate any phenomena of current collapse during the transient evolution of the GaN HEMT's internal trapping state. Hence, this result could have important implications on GaN HEMT-based PAs' linearizability for cellular and radar applications. Fig. 2 illustrates the result of the PA's characterization when compensated by the piecewise-SRH analog circuit.

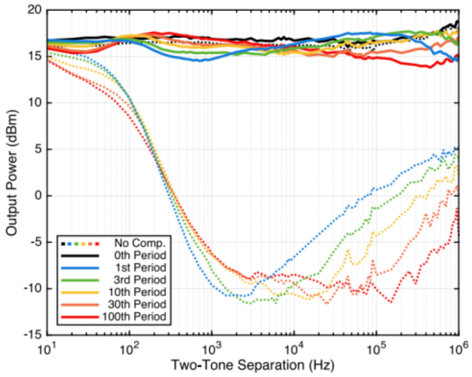

Fig. 2 Dynamic variation of the small-signal PA output power when compensated by the piecewise-SRH analog compensation circuit.

V. IMPACT STATEMENT AND CAREER PLAN

Receiving the MTT-S Graduate Fellowship award was certainly a motivation boost that re-enforced my already positive perspective on my PhD work plan and for that I am grateful.

In the short term, my goal is to make use of the specialized knowledge and skills obtained during my PhD to secure a position where these can be simultaneously useful and challenged. From the employer perspective, the MTT-S Graduate Fellowship could act as an important recognition to the quality of my PhD work. In the long term, the ambition is to contribute to the development of disruptive technologies, that can add significant value to the present but mostly to the far future.

REFERENCES

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