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Modeling of Trap Induced Dispersion of Large Signal Dynamic Characteristics of GaN HEMTs

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\begin{abstract}
We propose here a non-linear GaN HEMT model for CAD including a trapping effects description consistent with both small-signal and large-signal operating modes. It takes into account the dynamics of the traps and then allows to accurately model the modulated large signal characteristics that are encountered in telecommunication and radar signals. This model is elaborated through low-frequency S-parameter measurements complementary to more classical pulsed-IV characterizations. A 8x75μm AlInN/GaN HEMT model was designed and particularly validated in large-signal pulsed RF operation. It is also shown that thermal and trapping effects have opposite effects on the output conductance, thus opening the way for separate characterizations of the two effects.
\end{abstract}

\begin{keywords}
Trapping effects, thermal effects, low frequency S-parameters, non-linear model, RF pulsed operation.
\end{keywords}

\section{Introduction}
Gallium Nitride (GaN) High Electron Mobility Transistors (HEMT) on SiC are now recognized as good candidates for the development of a number of RF applications and notably Power Amplifiers (PA) for telecommunication and radars, due to their high breakdown voltage, their high cut-off frequency, and their high temperature capabilities. However, they are still subject to parasitic effects such as thermal effects and especially trapping effects. Those trapping effects have been extensively studied using a number of techniques such as pulsed measurements, load-pull measurements as well as frequency dispersion measurements. At the same time, models have been proposed that take those effects into account, and while the effects of traps are well taken into account in CW conditions, their impact on dynamic large signal characteristics remains difficult to understand. They manifest themselves under modulated signals such as RF pulses or telecommunication signals. Memory effects are the main consequence of those trapping effects. This paper is organized as follows: Section II describes the theoretical impact of traps on the average current obtained under pulsed load pull conditions. Section III presents the experiments performed on an AlInN/GaN S-Channel HEMT and the results obtained using a large signal non-linear electrothermal model taking into account the dynamics of the traps. Finally we conclude and draw some perspectives.

\section{Impact of traps on large signal characteristics}
Our convenient way to identify the impact of trapping effects is to monitor the average drain current of the transistor versus an increasing RF input power. It has already been reported in [1] and [2] that this drain current under class-FB conditions decreases as the input power increases, modulating the expected characteristics. Clearly this behavior cannot be explained by thermal behavior as far as the channel temperature-steps when the power increases and would lead, at least for moderate powers, to an average drain current rearrangement.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1.png}
\caption{Representation of the mechanism induced by traps on the average drain current.}
\end{figure}

Pulsed RF measurements were performed under DC bias on 3×3×3 AlInN/GaN and 6×6×6 AlInN/GaN HEMTs of 8x75μm2 for a large number of output loads. For all devices, we obtain the same shape of the average drain current which is summarized in Figure 1. The average current decrease is due to the trap capture, which increases at the gate and drain voltage excursions versus the input power for a CW measurement. Indeed, the number of trapped traps is roughly proportional to the maximum value of the drain-source voltage, because of the decay memory of the capture and emission time constants.
Modeling of Trap Induced Dispersion of Large Signal Dynamic Characteristics of GaN HEMTs

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Abstract—We propose here a non-linear GaN HEMT model for CAD including a trapping effects description consistent with both small-signal and large-signal operating modes. It takes into account the dynamics of the traps and allows to accurately model the modulated large signal characteristics that are encountered in telecommunication and radar signals. This model is elaborated through low-frequency S-parameter measurements and high-frequency time-domain measurements. A 24X75um AlGaN/GaN HEMT model was designed and particularly validated in large-signal pulsed RF operation. It is also shown that thermal and trapping effects have opposite effects on the output conductance, thus opening the way for separate characterization of the two effects.

I. INTRODUCTION

GaAs N-channel (GaN) High Electron Mobility Transistors (HEMT) on SiC are now recognized as good candidates for the development of a number of RF applications and notably Power Amplifiers (PA) for telecommunications and radars, due to their high breakdown voltage, high cutoff frequency and high thermal stability. However, they are still subject to parasitic effects such us thermal effects and especially trapping effects. Those trapping effects have been extensively studied using a number of techniques such as pulsed measurements, load pull measurements as well as frequency dispersion measurements. At the same time, models have been proposed that take those effects into account [1,2,3], and while the effects of traps are well taken into account in CW conditions, their impact on dynamic large signal characteristics remains difficult to modelize. They manifest themselves under modulated signals such as RF pulses or telecommunications signals. Memory effects are the main consequence of those trapping effects. In this paper we propose to investigate the dynamics of those trapping effects using large signal pulsed load pull measurements as well as frequency dispersion measurements. It will be shown that a consistent model provides a description that is able to describe the full behavior of GaN transistors. The paper is organized as follows: Section II describes the theoretical impact of traps on the average current obtained under pulsed load pull conditions. Section III presents the measurements performed on an AlGaN/GaN 24X75um HEMT and the results obtained using a large signal non-linear electrothermal model taking into account the dynamics of the traps. Finally we conclude and draw some perspectives.

I. IMPACT OF TRAPS ON LARGE SIGNAL CHARACTERISTICS

One convenient way to identify the impact of trapping effects is to monitor the average drain current of the transistor versus an increasing RF input power. It has already been reported in [1] and [3] that this drain current under class-AB condition decreases as the input power increases, contradicting the expected characteristics. Clearly this behavior cannot be explained by thermal behavior as far as the channel temperature-steps when the power increases and would lead, at least for moderate powers, to an average drain current enhancement.

\begin{abstract}
We propose here a non-linear GaN HEMT model for CAD including a trapping effects description consistent with both small-signal and large-signal operating modes. It takes into account the dynamics of the traps and allows to accurately model the modulated large signal characteristics that are encountered in telecommunication and radar signals. This model is elaborated through low-frequency S-parameter measurements and high-frequency time-domain measurements. A 24X75um AlGaN/GaN HEMT model was designed and particularly validated in large-signal pulsed RF operation. It is also shown that thermal and trapping effects have opposite effects on the output conductance, thus opening the way for separate characterization of the two effects.
\end{abstract}
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Abstract—We propose here a non-linear GaN HEMT model for CAD including a trapping effects description consistent with both small- and large-signal operating modes. It takes into account the dynamics of the traps and then allows to accurately model the modulated large signal characteristics that are encountered in telecommunication and radar signals. This model is elaborated through low-frequency S parameter measurements complemented to more classical pulsed IV characterization. A validation of the GaN HEMT model was performed and particularly validated in large signal pulsed RF operation. It is also shown that thermal and trapping effects have opposite effects on the output conductance, thus opening the way for separate characterizations of the two effects.

1. INTRODUCTION

Identification of the source of the drift in this introductory section is required. Specifically, please cite a reference for the opening sentence on Gallium Nitride HEMT.

Gallium Nitride (GaN) High Electron Mobility Transistors (HEMT) on SiC are now recognized as good candidates for the development of a number of RF applications and notably Power Amplifiers (PA) for telecommunications and radar, due to their high breakdown voltage, their high current frequency as well as their high temperature capabilities. However, they are still subject to various effects such as thermal effects and especially trapping effects. These trapping effects have been extensively studied using a number of techniques such as pulsed measurements, kink/pull measurements as well as frequency dispersion measurements. At the same time, models have been proposed that take these effects into account [1,2,3], and while the effects of traps are well taken into account in CW conditions, their impacts on dynamic large signal characteristics remain difficult to understand. They manifest themselves under modulated signals such as RF pulses or telecommunications signals. Memory effects are the main consequence of these trapping effects. In this paper, we propose to the dynamics of those trapping effects using large signal pulsed RF measurements as well as low frequency dispersion measurements. It will be shown that a consistent nonlinear model can be obtained that allows to describe the full dynamic behavior of GaN transistors. The paper is organized as follows: Section II describes the theoretical impact of traps on the average current obtained under pulsed RF pull conditions. Section III presents the measurements performed on an AlGaN/GaN HEMT and the results obtained using a large signal nonlinear device model taking into account the dynamics of the traps. Finally, we conclude and draw some perspectives.

2. IMPACT OF TRAP ON LARGE SIGNAL CHARACTERISTICS

One convenient way to identify the impact of trapping effects is to monitor the average drain current of the transistor as an increasing RF input power. It has already been reported in [1] and [7] that this drain current under class AB conditions increases to a linear power increase, contradicting the expected characteristics. Clearly, this behavior cannot be explained by thermal behavior as far as the channel temperature scales when the power increases and would lead, at least for moderate powers, to an average drain current enhancement.

3. EXPERIMENTAL RESULTS

Fig. 1. Representation of the mechanism induced by traps on the average drain current.

Pulsed RF measurements were performed under DC bias on AlGaN/GaN and InAlN/GaN HEMTs of 8x75 µm2 for a large number of output loads. For all devices, we obtain the same shape of the average drain current which is characterized in Figure 1. The average current decrease is due to the trap capture, which increases as the gate to drain voltage...
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\textbf{Theorem} x.yz. Delete this text and write theorem statement here.

\begin{proof}
Blah, blah, blah. Here is an example of the \texttt{align} environment:

%Note 1: The \texttt{*} tells LaTeX not to number the lines. If you remove the \texttt{*}, be sure to remove it below, too.

%Note 2: Inside the align environment, you do not want to use $-$ signs. The reason for this is that this is already a math environment. This is why we have to include \texttt{\textit{it}} around any text inside the align environment.

\begin{align*}
\sum_{i=1}^{k+1} i &= \left( \sum_{i=1}^{k} i \right) + (k + 1) \\
&= \frac{k(k + 1)}{2} + k + 1 \\
&= \frac{k(k + 1)}{2} + \frac{2(k + 1)}{2} \\
&= \frac{(k + 1)(k + 2)}{2} \\
&= \frac{(k + 1)((k + 1) + 1)}{2}.
\end{align*}

\end{proof}

\begin{proof}
Let \( n \in \mathbb{Z} \). Then yada yada.

\begin{proof}
Blah, blah, blah. I'm so smart.
\end{proof}

\end{proof}
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