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# Identifying the spatial position and properties of traps in GaN HEMTs using current transient spectroscopy

Xiang Zheng, Shiwei Feng *, Yamin Zhang, Junwei Yang

*Institute of Semiconductor Device Reliability Physics, Beijing University of Technology, Beijing 100124, China*

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ABSTRACT

Time constant spectra are extracted from current transients based on the Bayesian deconvolution and used to characterize traps in GaN high-electron mobility transistors. Two kinds of traps with different time constants in an actual device were identified in the AlGaN barrier layer and the GaN layer, respectively. In particular, the trapping process in the AlGaN barrier layer was identified at the region near the drain side under gate contact. Trapping mechanisms of both two traps are discussed. Additionally, we observe that the trap in the AlGaN barrier layer requires sufficient electric field to activate the trapping process and a high drain voltage ($V_{ds}$) accelerates the trapping processes both in the AlGaN barrier layer and the GaN layer. In addition, detrapping experiments with different filling conditions were performed to confirm their spatial positions. The influence of self-heating is excluded during the experiment by keeping the power density at a very low level, and the trapping effect is the sole factor accounting for the current transients.



## 1. Introduction

The reliability problem of current collapse associated with GaN-based high-electron mobility transistors (HEMTs) restricts their wide application. Current collapse results in an actual output power that is much lower than the theoretical value, which arises from what is known as RF dispersion that occurs in high frequency applications [1]. Many possible mechanisms of current collapse have been discussed [2–7] and it is widely accepted that trapping effects play an important role in this problem.

At present, primary methods of measuring and representing traps are deep-level transient spectroscopy (DLTS) [8,9], electrical lag measurements [10], low frequency noise (LFN) measurements [11,12] and frequency-dependent capacitance and conductance analysis [13]. However, measurements are still lacking and there is still no unified model of the effect of traps. Recently, current transients were studied [14,15] because they contain a lot of information on traps.

In this paper, we present a new method to extract the time constants from the current transients. By analyzing these time constant spectra, we identified the spatial position of traps based on the trapping transients. This method is completely non-destructive and needs no specialized equipment. It can also provide the action time of traps and the degree to which a trap contributes to the decline in the drain current, which can be used to study the behaviors of traps.

* Corresponding author.
*E-mail address:* shwfeng@bjut.edu.cn (S. Feng).

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## 2. Experimental details

### 2.1. Device

The cross-section view and top view of the device used in this work are shown in Fig. 1 (a) and (b), respectively. This device was grown on a 4H-SiC substrate using metal-organic chemical vapor deposition, which was procured from Science and Technology on Monolithic Integrated Circuits and Modules Laboratory, Nanjing Electronic Devices Institute, China. The AlGaN/GaN HEMTs consists of a 1.5 μm GaN channel layer, 1 nm AlN interfacial layer and 25 nm un-doped AlGaN barrier layer. SiN was used as a passivation layer. The Al composition was chosen to be 25%. Ti/Al/Pt/Au was used as source/drain ohmic electrodes and Ni/Au was used as a Schottky gate. The source-to-gate spacing, gate-to-drain spacing, gate length, and gate wide were 2.5, 2, 1, and 200 μm, respectively. The device was composed of 10 fingers with the threshold voltage, maximum drain current and max transconductance of −2.1 V, 423 mA/mm and 235 mS/mm, respectively.

### 2.2. Current transient

A current transient is affected by two major factors: self-heating and trapping effects [15–18]. Previous studies [16–18] have shown that the drain current declines as the temperature increases because of a high power density. Also, trapping behaviors cause a decline in the current by capturing electrons whereas detrapping behaviors cause an increase in drain current by releasing electrons [15]. Therefore, we can acquire information about the traps from the current transients after excluding the self-heating effect.

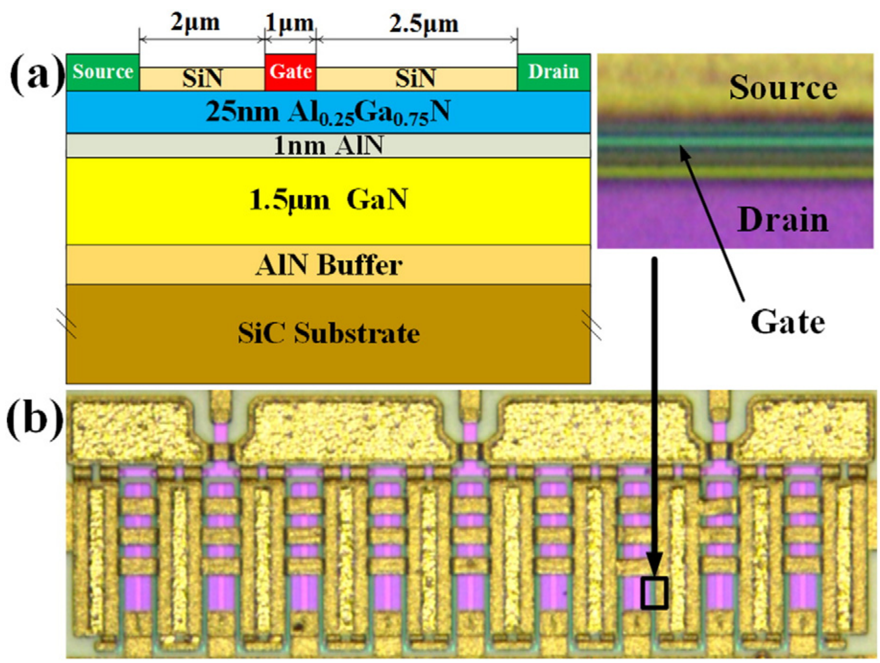


**Fig. 1.** Structure of the device. (a) Cross-section view. (b) Top view.

We assumed that a drain current transient involves several independent trapping and detrapping processes, and each process decays exponentially with time [15]. So, the drain current transient can be expressed as

$$I_{DS}(t) = \sum_{i=0}^{n} \Delta I_i \exp\left(-\frac{t}{\tau_i}\right) + I_\infty \tag{1}$$

where $I_{DS}(t)$ is the drain current transient, $t$ is the time, $\tau_i$ is the time constant of the $i$th trap, $n$ is the number of traps with different time constants, $\Delta I_i$ is the corresponding coefficient, and $I_\infty$ is the current in the steady state. The rationale behind this assumption has been explained previously [15]. Beyond its theoretical rationality, this assumption fits the experimental results very well.

In our experiments, the current transients are measured by Agilent B1500A semiconductor parameter analyzer and the test mode is I/V-t sampling.

*2.3. A new method for the extraction of the time constants*

The calculation of the time constants of the current transients is necessary for the following analysis. There are several methods for the evaluation of the time constants [15,19], which were already discussed in [14]. In this paper, we proposed a new method for the extrapolation of the time constants of traps, which is used to extract the heat time constant spectrum [20].

First, a logarithmic variable for the time is introduced because of the wide range of time constants (from 1 ms to 1 ks in the experiments):

$$z = \ln t. \tag{2}$$

We define the time constant spectrum of traps as the following expression:

$$\Delta \mathrm{I}(z) = \lim_{\delta z \to 0} \frac{magnitudes related\ to\ the time constants between\ z\ and\ z+\delta}{\delta z} \tag{3}$$

$\Delta I(z)$ is the time constant spectrum. Now the current transient $I_{DS}(t)$ can be expressed as

$$I_{DS}(t) = \int_{-\infty}^{\infty} \Delta \mathrm{I}(\tau)\left(\exp\left(-\frac{t}{\exp(\tau)}\right)\right) d\tau + I_\infty. \tag{4}$$

Compared with the Eq. (1), this is a generalization of the drain current transient. Using Eq. (2), the current transient can be expressed as

$$I_{DS}(z) = \int_{-\infty}^{\infty} \Delta \mathrm{I}(\tau)(\exp(-\exp(z-\tau))) d\tau + I_\infty. \tag{5}$$

This is a convolution-type integral equation for the unknown $\Delta I(\tau)$. After differentiating both sides of expression (5) with respect $z$ we can obtain

$$\frac{d}{dz} I_{DS}(z) = -\int_{-\infty}^{\infty} \Delta \mathrm{I}(\tau)(\exp(z-\tau-\exp(z-\tau))) d\tau. \tag{6}$$

Here we define a function $W(z)$ as following:

$$W(z) = \exp(z - \exp(z)). \tag{7}$$

Considering the Eq. (6), $\frac{d}{dz} I_{DS}(z)$ can be expressed as

$$\frac{d}{dz} I_{DS}(z) = -\Delta \mathrm{I}(z) \otimes W(z) \tag{8}$$

where $\otimes$ is the symbol of the convolution operation. And the time constant spectrum $\Delta \mathrm{I}(z)$ can be expressed as

$$\Delta \mathrm{I}(z) = \left(-\frac{d}{dz} I_{DS}(z)\right) \otimes^{-1} W(z) \tag{9}$$

Finally, the deconvolution should be accomplished to acquire the time constants of traps and we choose the Bayesian deconvolution as our means [21–23], which can effectively filter out noise in the