Microelectronics Reliability 93 (2019) 57–60

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

A voltage-transient method for characterizing traps in GaN HEMTs

Xiang Zheng, Shiwei Feng*, Yifu Gao, Yamin Zhang, Yunpeng Jia, Shijie Pan

College of Microelectronics, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Keywords:
GaN
High electron mobility transistors (HEMTs)
Trapping effect
Voltage transient

ABSTRACT

Trapping effects in GaN HEMTs still limit their performance. The current-transient methodology has shown advantages in characterizing traps in the device. However, the voltage drift may cause errors in measurements with high accuracy requirements. In this paper, we present a methodology to characterize traps in GaN HEMTs using the voltage-transient measurements. We demonstrate the advantages of this method in terms of simplicity and effectiveness. In particular, it avoids the said problem due to the optimized measuring circuit. With this method, we have identified the time constants and energy levels of traps in the AlGaN barrier layer and the GaN buffer layer, respectively, in the devices. Their trapping and de-trapping mechanisms were also demonstrated at various temperature measurements. A classic exponential dependence of the degradation rate on the channel current was identified.

1. Introduction

The high electron mobility transistors based on GaN are of great interest for high power and high operating frequency devices. However, the reliability of high-electron-mobility transistors (HEMTs) remains hindered by trapping effects, restricting their wide application [1].

Many methods have been proposed for demonstrating traps in GaN HEMTs, including deep-level transient spectroscopy (DLTS) [2,3], frequency-dependent capacitance and conductance analysis [4], and low-frequency noise measurement [5,6]. Besides them, a current-transient methodology for analyzing traps has shown its advantages in long-term stress experiments and in identifying the properties of traps in devices [7].

The traps' time constants, energy levels, spatial positions and the degree to which the trap changes the channel current [8–10] can be demonstrated using the current transient spectroscopy. Commercial Semiconductor analyzers were used to complete these measurements. However, sometimes a special home-made circuit is necessary to meet some requirements like larger time decades. For these circuits, the drain of the DUT (device under test) is connected to a power supply through a load resistor (R_{load}) and the current transient was calculated from the change in voltage across the load resistor over time as shown in Fig. 1(a).

However, the drain-source voltage (V_{DS}) is not equal to the applied value of the supply because of the R_{load}. It needs an additional calculation to apply the expected V_{DS} to devices. Second, the drain–source voltage cannot be constant due of the variation of the current. A compromise is to choose a small load resistance [11]. However, it may cause a decrease in the signal–to-noise. In addition, to exclude the self-heating effect caused by the high power, in most measurements the drain-source currents (I_{DS}) were at low level, which also cause the difficulties in measuring accuracy. For devices with smaller size and shorter gate width, it is much harder to reduce errors. Another way to avoid the voltage drift is to add a feedback circuit. However, it will increase the complexity of the test circuit and decrease the sampling frequency.

In this paper, we proposed an alternative method to characterize the traps in GaN HEMTs using the voltage transient under a constant drain current. Fig. 1(b) shows its circuit connection. It will be shown that it has all the advantages of the above method and it avoids voltage drifts during the measurements, which will be discussed in Section 2 in detail. It also removes the need to calculate the real applied V_{DS}. This method provides an effective way to characterize the trapping effect especially when the effect of the R_{load} on the results is significant in some cases. We have applied this method to different kinds of devices to benchmark its effectiveness. Both trapping and de-trapping behaviors can be demonstrated from the experiments clearly and simply. The degradation rate caused by the traps in the vicinity of the channel, for the first time, was observed to exhibit a classic exponential dependence on the channel current.

2. Experimental results

The GaN HEMTs used in this work were Cree's CGH40006P. The

* Corresponding author.
E-mail addresses: shwfeng@bjut.edu.cn (S. Feng), yaminzhang@bjut.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.microrel.2018.12.009
Received 25 September 2018; Received in revised form 18 December 2018; Accepted 27 December 2018
Available online 10 January 2019

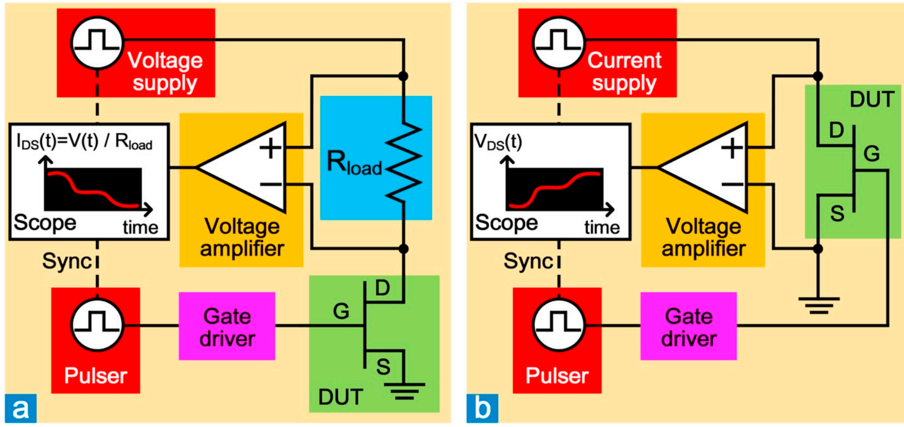

Fig. 1. (a) The diagram of the circuit connection for current-transient measurements and an R_{load} is necessary for measuring the current transients. (b) The diagram of the circuit connection for voltage-transient measurements.

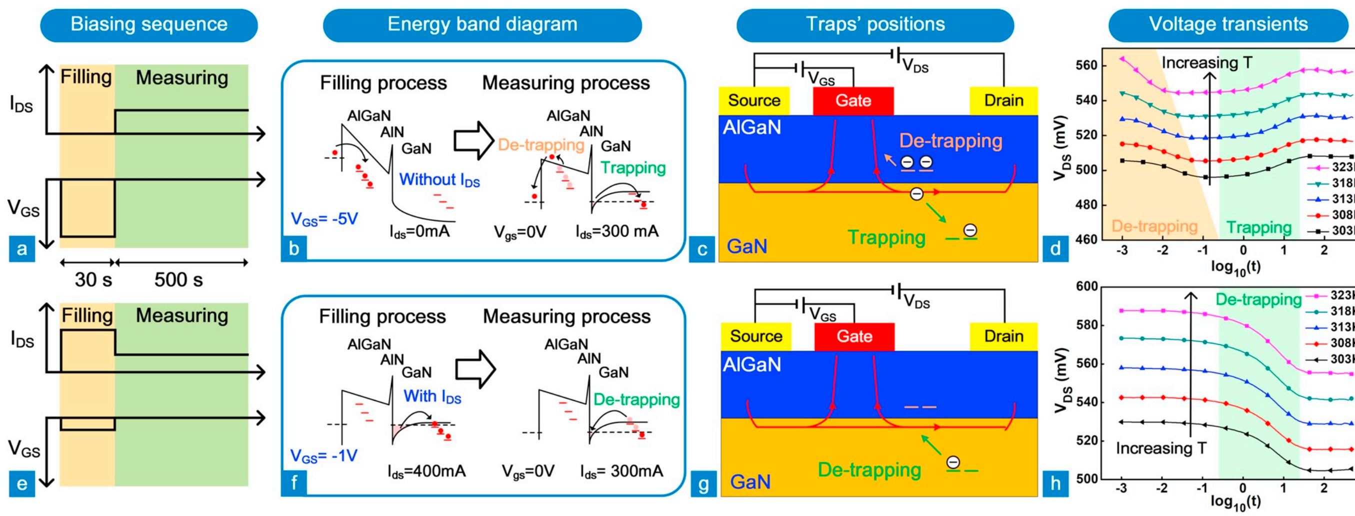

Fig. 2. (a) The biasing sequence with a 30-s-long filling pulse for case 1. (b) The energy band diagram in filling and measuring processes for case 1. (c) Two traps' positions and their behaviors during the measuring process for case 1. (d) The voltage transients at various temperatures under a fixed I_{DS} for case 1. (e) The biasing sequence with a 30-s-long filling pulse for case 2. (f) The energy band diagram in filling and measuring processes for case 2. (g) Two traps' spatial positions and their behaviors during the measuring process for case 2. (h) The voltage transients at various temperatures under a fixed I_{DS} for case 2.

drain-source voltage transients were measured with a fixed I_{DS} of 300 mA after a 30-s-long filling pulse. There are two cases for the filling processes with the (V_{GS}; I_{DS}) = (−5 V; 0 A) and (V_{GS}; I_{DS}) = (−1 V; 400 mA), respectively, as shown in Fig. 2(a) and (e). For the former (named case 1), the filling pulse aims to fill traps in the AlGaN barrier layer, i.e., whose charge trapping could be promoted by high reverse gate and the subsequent high gate leakage current primarily. For the latter (named case 2), the filling pulse aims to fill traps who capture the electrons from the 2DEG directly.

For case 1, traps in the vicinity of the channel cannot be trapped during the 30-s-long filling pulse. So, they will show a trapping behavior in the subsequent measuring process, which is caused by the measuring I_{DS} of 300 mA. Otherwise, traps who capture electrons from the gate leakage current can be filled by the filling pulse with a high reverse gate voltage and they will show a de-trapping behavior in the measuring process. Fig. 2(b) and (c) show detailed information about the trapping and de-trapping mechanisms in case 1.

For case 2, the 30-s-long pulse with a high V_{DS} and high I_{DS} aims to fill traps in the vicinity of the channel. In particular, the temperature rise was lower than 2 °C according to the chip's thermal resistance of 9.5 K/W, which can be ignored. For the traps in the AlGaN barrier layer, because both filling and measuring process cannot apply the available charges to be captured, they should not appear in this case. Fig. 2(f) and (g) show detailed information about the trapping and de-trapping mechanisms in case 2.

Fig. 2(d) shows the measured curves with a measuring I_{DS} of 300 mA at various temperatures in case 1. Traps in the AlGaN layer (named Trap1) with a temperature-dependent de-trapping time constant of millisecond level and traps near the channel in the GaN layer (named Trap2) with a temperature-independent trapping time constant of second level were observed, respectively.

Fig. 2(h) shows the measured curves with a measuring I_{DS} of 300 mA at various temperatures in case 2. Trap1 was not observed in both filling and measuring processes as expected. Trap2 showed the de-trapping behaviors after being filled. Interestingly, both trapping and de-trapping time constants of Trap2 were temperature-independent, which will be discussed in detail in the following.

The corresponding time constant spectra were calculated from the voltage transients using $\partial I_{DS}/\partial \log(t)$ as shown in Fig. 3. A fitting of transient data by a polynomial function before differentiation can help to acquire smoother curves [12]. However, the voltage transients were differentiated with respect to log (t) without fitting for more accurate peaks and the signal-to-noise ratio were acceptable.

Fig. 3(a) shows the time constant spectra for case 1 at temperatures from 303 K to 323 K. Trap1 with shorter time constant shows a de-trapping behavior while Trap2 with a time constant of 7.2 s shows a

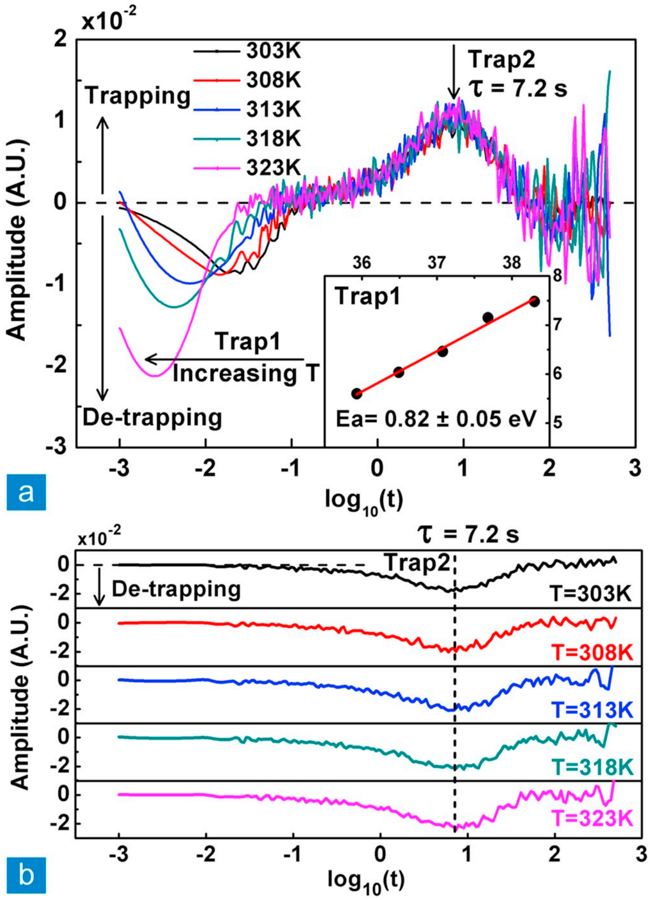

Fig. 3. (a) The corresponding time constant spectra of the measured voltage transients for case 1. Trap1's de-trapping behavior was temperature-dependent while Trap2's trapping behavior was temperature-independent. (Inset) Arrhenius plots of Trap1. (b) The corresponding time constant spectra of the measured voltage transients for case 2. Trap2's de-trapping behavior was temperature-independent.

trapping behavior. Arrhenius plots of Trap1 were calculated as shown in the inset and an energy level (E_a) of 0.82 eV ± 0.05 eV was acquired. This energy level could be found in [13,14], which could be ascribed to the traps in the AlGaN barrier layer. The trapping behavior of Trap2 was insensitive to temperature. The appearance of Trap2 at a low V_{DG} suggests that it is unlikely to be a hot-electron trapping process inside the AlGaN or deep into the GaN buffer layer. In addition, the time constant also did not show a dependence on V_{DG}, indicating that this trapping process occurs in the vicinity of channel [7].

Fig. 3(b) shows the time constant spectra for case 2 at temperatures from 303 K to 323 K. In this case, the reverse gate voltage of −1 V and the corresponding reverse gate current were very low and hard to induce the trapping behavior of Trap1 during the filling process. A higher I_{DS} of 400 mA was applied to fill Trap. So, in the recovery process only Trap2 shows a de-trapping behavior with a temperature-independent time constant of 7.2 s which is highly consistent with its trapping time constant in case 1, indicating that they are exact inverse processes of each other.

An exponential dependence of the measuring voltage on the degradation rate was observed in previous literature [15]. In this work, we examined the channel current dependence on the amplitudes. Interestingly, we found that the amplitudes were exponentially proportional to the measuring I_{DS} as shown in Fig. 5. As far as we know, this is the first time that an exponential relationship between the channel current and the corresponding amplitude is acquired. So, we applied this experiment to a different sample to benchmark this phenomenon.

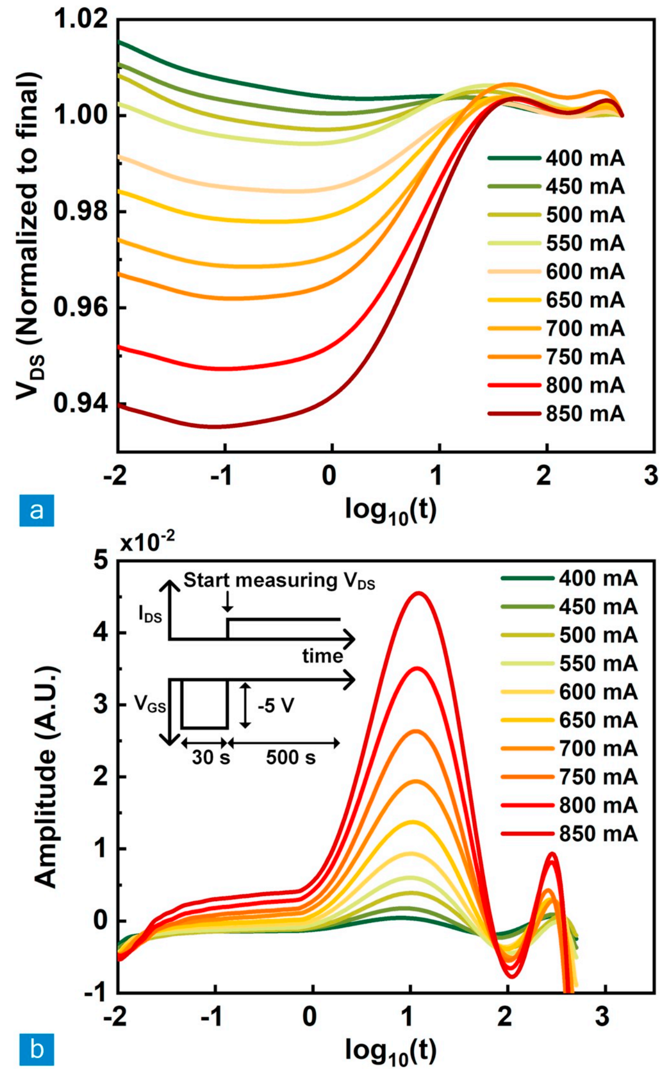

Fig. 4. (a) The voltage transients of the Qorvo's T2G6001528-SG in case 1 with measuring current varied from 400 mA to 850 mA. (b) The biasing sequence and the corresponding time constant spectra.

Qorvo's T2G6001528-SG was used and the same experiments in case 1 were carried out at varied measuring current from 400 mA to 850 mA as shown in Fig. 4(a). Expected trapping behaviors in the channel region were also identified and the corresponding time constant spectra were as shown in Fig. 4(b). Notice that the transients were fitted by a polynomial function [12] to make the curves smoother and the amplitudes easier to acquire. Measuring drain currents lower than 400 mA cannot induce a trap-dominated behavior, i.e. a rising part in the recovery transient because the corresponding drain-source voltage was lower than 0.4 V.

Fig. 5 shows the peak amplitudes, i.e. the degradation rate of both samples under various I_{DS}. The insets show their output curves with V_{GS} of 0 V. Both of them were fitted by $Ae^{I_{DS}/B} + y_0$ with the Adj. R-Square of 0.9983 and 0.9996, respectively, strongly indicating that this trapping behavior was directly related to the channel current. For a trapping process if the carriers have to overcome an energy barrier, as the rate of transport through the barrier is proportional to the carrier population, which follows an exponential dependence [7]. In addition, the ratio of factor B of the two samples is almost reciprocal to the ratio of their channel resistances in the linear region. It provides a way to predict the degradation rate caused by the traps in the channel region. Notice that this classic exponential dependence on the channel current was measured in the linear region, where the highest temperature rises

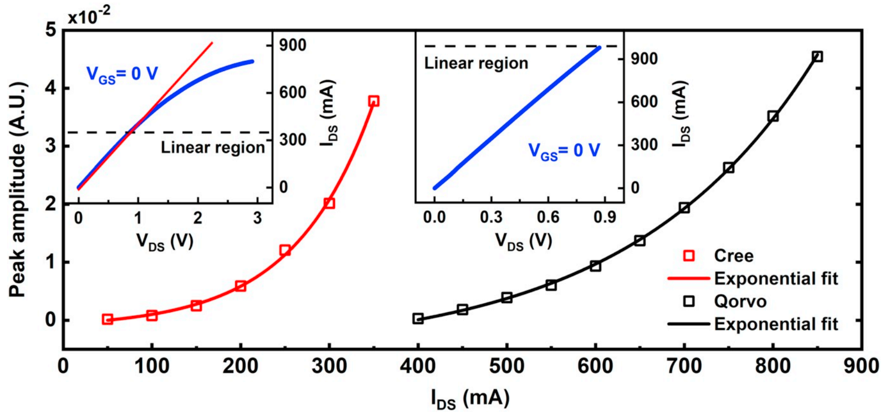

Fig. 5. Channel current dependence on the amplitudes of two samples. (Inset) Their output curves with V_{GS} of 0 V. The dependences were strongly exponential.

were calculated within 2.9°C and 4.3°C, respectively, according to their thermal resistances of 9.5 K/W and 6.7 K/W. So, their effects on transients were extremely limited.

3. Conclusion

A voltage-transient methodology for analyzing traps in GaN HEMTs was proposed. Two traps named Trap1 and Trap2 with different time constants were identified. Their trapping and de-trapping behaviors were demonstrated using this method. The de-trapping behavior of Trap1 needs to overcome an energy barrier while both trapping and de-trapping behaviors of Trap2 are not thermally activated. This method has the same advantages in extracting time constants and energy levels of traps as the current-transient methodology. However, it avoids the voltage drifts during the measuring process compared to the current-transient method. It makes more accurate measurements possible and provides a simple and new approach to characterize traps in GaN HENTs. For the first time, we found a perfect exponential dependence of the amplitudes of traps in the channel region on the channel current. This method makes it possible to study the relationship between the trapping effect and the current exactly.

Acknowledgment

This work was supported by National Natural Science Foundation of China under Grant 61774011.

The authors would like to thank Prof. Meneghesso of the University of Padova and Dr. Bisi of Transphorm Inc. for their help in this work.

References

[1] S.C. Binari, P.B. Klein, T.E. Kazior, Trapping effects in GaN and SiC microwave FETs, Proc. IEEE 90 (6) (Jun. 2002) 1048–1058.
[2] A. Sasikumar, A.R. Arehart, S. Martin-Horcajo, M.F. Romero, Y. Pei, D. Brown, F. Recht, M.A. di Forte-Poisson, F. Calle, M.J. Tadjer, S. Keller, S.P. DenBaars, U.K. Mishra, S.A. Ringel, Direct comparison of traps in InAlN/GaN and AlGaN/GaN high electron mobility transistors using constant drain current deep level transient spectroscopy, Appl. Phys. Lett. 103 (3) (Jul. 2013) 033509-1–033509-4.
[3] M. Marso, M. Wolter, P. Javorka, P. Kordoš, H. Lüth, Investigation of buffer traps in an AlGaN/GaN/Si high electron mobility transistor by backgating current deep level transient spectroscopy, Appl. Phys. Lett. 82 (4) (Jan. 2003) 633–635.
[4] R. Stoklas, D. Gregušová, J. Novák, A. Vescan, P. Kordoš, Investigation of trapping effects in AlGaN/GaN/Si field-effect transistors by frequency dependent capacitance and conductance analysis, Appl. Phys. Lett. 93 (12) (Sept. 2008) 124103-1–124103-3.
[5] A. Sozza, C. Dua, E. Morvan, M.A. diForte-Poisson, S. Delage, F. Rampazzo, A. Tazzoli, F. Danesin, G. Meneghesso, E. Zanoni, A. Curutchet, N. Malbert, N. Labat, B. Grimbert, J.-C. De Jaeger, Evidence of traps creation in GaN/AlGaN/GaN HEMTs after a 3000 hour on-state and off-state hot-electron stress, IEEE IEDM Tech. Dig, Dec. 2005, pp. 590–593.
[6] P. Valizadeh, D. Pavlidis, Effects of RF and DC stress on AlGaN/GaN MODFETs: a low-frequency noise-based investigation, IEEE Trans. Device Mater. Reliab. 5 (3) (Sept. 2005) 555–563.
[7] J. Joh, J.A. Del Alamo, A current-transient methodology for trap analysis for GaN high electron mobility transistors, IEEE Trans. Electron Devices 58 (1) (Jan. 2011) 132–140.
[8] D. Bisi, M. Meneghini, C. de Santi, A. Chini, M. Dammann, P. Brückner, M. Mikulla, G. Meneghesso, E. Zanoni, Deep-level characterization in GaN HEMTs-part I: advantages and limitations of drain current transient measurements, IEEE Trans. Electron Devices 60 (10) (Oct. 2013) 3166–3175.
[9] X. Zheng, S. Feng, Y. Zhang, J. Yang, Identifying the spatial position and properties of traps in GaN HEMTs using current transient spectroscopy, Microb. Releases 63 (Aug. 2016) 46–51.
[10] X. Zheng, S. Feng, Y. Zhang, Y.X. He, Y. Wang, A new differential amplitude Spectrum for analyzing the trapping effect in GaN HEMTs based on the drain current transient, IEEE Trans. Electron Devices 64 (4) (Apr. 2017) 1498–1504.
[11] D. Bisi, A. Stocco, M. Meneghini, F. Rampazzo, A. Cester, G. Meneghesso, E. Zanoni, High-voltage double-pulsed measurement system for GaN-based power HEMTs, Reliability Physics Symposium, IEEE International, Jul. 2014, pp. CD.11.1–CD.11.4.
[12] M. Tapajna, R.J.T. Simms, Y. Pei, U.K. Mishra, M. Kuball, Integrated optical and electrical analysis: Identifying location and properties of traps in AlGaN/GaN HEMTs during electrical stress, IEEE Electron Device Lett. 31 (7) (Jul. 2010) 662–664.
[13] A. Benvegnù, S. Laurent, O. Jardel, J.L. Muraro, M. Meneghini, D. Barataud, G. Meneghesso, E. Zanoni, R. Quéré, Characterization of defects in AlGaN/GaN HEMTs based on nonlinear microwave current transient spectroscopy, IEEE Trans. Electron Devices 64 (5) (May 2017) 2135–2141.
[14] J. Osaka, Y. Ohno, S. Kishimoto, K. Maezawa, T. Mizutani, Deep levels in *n*-type AlGaN grown by hydride vapor-phase epitaxy on sapphire characterized by deep-level transient spectroscopy, Appl. Phys. Lett. 87 (22) (Nov. 2005) 222112-1–222112-3.
[15] S.D. Mertens, J.A. del Alamo, Electrical degradation of InAlAs/InGaAs metamorphic high-electron mobility transistors, IEEE IEDM Technol. Dig. (Dec. 2001) 193–196.