Experimental and Numerical Analysis of Hole Emission Process From Carbon-Related Traps in GaN Buffer Layers

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***Abstract*— The role of carbon-related traps in GaN-based ungated high-electron mobility transistor structures has been investigated both experimentally and by means of numerical simulations. A clear quantitative correlation between the experimental data and numerical simulations has been obtained. The observed current decrease in the tested structure during backgating measurements has been explained simply by means of a thermally activated hole-emission process with $E_A = 0.9$ eV, corresponding to the distance of the acceptor-like hole-trap level from the GaN valence band. Moreover, it has been demonstrated by means of electrical measurements and numerical simulations that only a low percentage of the nominal carbon doping levels induces the observed current reduction when negative substrate bias is applied to the tested structure.**

***Index Terms*— Carbon doping, numerical simulation, trapping phenomena, wide bandgap semiconductors.**

I. Introduction

GaN-BASED high-electron mobility transistors (HEMTs) are of increasing interest for the development of low ON-resistance and low-switching losses devices for power switching applications [1], [2]. One of the mandatory steps in order to realize an excellent solid-state power switch is the formation of a semi-insulating (SI) buffer layer that has to be able to both reduce the device leakage currents in the OFF-state conditions and withstand the large device operating voltages. Carbon doping, which induces a complex set of acceptor trap levels located in the lower half of the GaN bandgap, has been proposed [3], and it is widely used [4]–[6] in order to fabricate high insulating buffer layers. Nevertheless, its introduction has also been linked to device dynamic ON-resistance increase [4], [5], which represents a strong limitation in order to fully exploit the GaN-based devices capability for efficient power switching operation.

In the last years, several papers have been dealing with the understanding and modeling of trapping phenomena that are likely to be related to carbon doping. Numerical simulations presented in [7] showed that a C-doped GaN buffer can cause a significant current collapse in GaN-based devices due to the two-dimensional electron gas (2DEG) depletion induced by the negative charge build-up occurring in the C-doped GaN buffer when the devices are subjected to high operating voltages. The assumption of an acceptor trap located at 0.9 eV from the GaN valence band (VB) was also able to reproduce by means of numerical simulations the current collapse in GaN Schottky barrier diode grown on C-doped GaN buffer [8]. Drain current transient measurements carried out on ungated AlGaN/GaN structures with C-doped GaN buffer layer have shown the presence of a 0.86-eV thermally activated current decrease when applying moderate negative substrate voltage levels, which has been explained by means of hole conduction in the GaN VB [9]. Recently, it was shown experimentally in [10] that the device ON-resistance recovery after the OFF-state high bias conditions in C-doped GaN buffer devices was thermally activated with an $E_A = 0.93$ eV, and it was suggested that this phenomena might be related to the emission of electrons captured in carbon-related buffer traps during the OFF-state high bias conditions.

Nevertheless, a clear and quantitative correlation between experimental and numerical simulation results concerning trapping phenomena linked to C-doped GaN buffer layers has not yet been presented. The aim of this paper is thus to study both by experimental measurements and numerical simulations the role of carbon doping in GaN layers in order to gain insights into the trap levels formed by the incorporation of carbon as well as to provide quantitative results concerning the simulation parameters that have to be adopted in order to consider the carbon-related trap levels. This last point is particularly critical in order to use numerical simulations as a tool for the prediction and/or evaluation of GaN-based power HEMTs operation.

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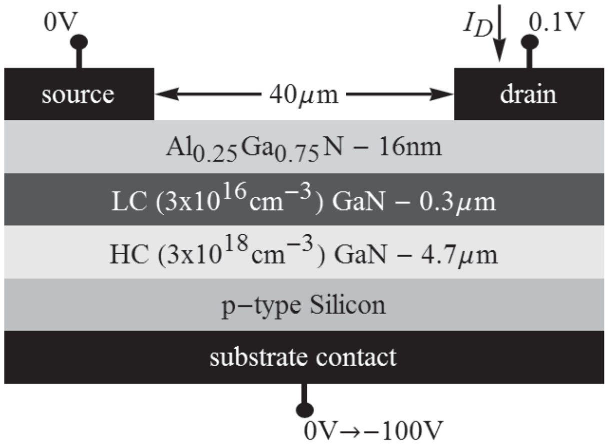

Fig. 1. Cross section of the tested and simulated ungated AlGaN/GaN HEMT structures. Bias voltages applied during the drain current transient measurement after applying a negative voltage step from 0 to −100 V to the wafer substrate are also reported.

This paper is thus organized as reported as follows.

Section II will briefly describe the devices used in this paper and the experimental measurements carried out. In particular, the main results obtained is that when applying a negative substrate voltage to an ungated AlGaN/GaN structure, a thermally activated drain current decrease is observed with $E_A = 0.9$ eV.

Section III describes the setup of the numerical simulations carried out in order to explain the experimental data. Three different trap configuration scenarios will be considered.

Section IV presents the numerical simulation results obtained by considering the three trap scenarios. Only when an acceptor trap level at 0.9 eV from GaN VB is considered, Scenario B, a qualitative agreement between the simulated and measured data can be observed.

Finally, Section V deals with the quantitative fitting by means of the numerical simulations of the experimental data. It will be shown that a nice quantitative fitting can be obtained only if a trap concentration significantly lower than the nominal C-doping level is considered.

II. Experimental Results

Experimental measurements and numerical simulations presented were carried out on ungated AlGaN/GaN HEMTs structures grown by metal–organic chemical vapor deposition on a Si(111) p-type substrate with a source/drain spacing of 40 μm (see Fig. 1). The epilayers consisted of a nucleation layer, a 4.7-μm-thick GaN buffer with a 3×10^{18} cm^{-3} carbon doping concentration (high-carbon (HC)), and a 0.3-μm-thick GaN layer with a 3×10^{16} cm^{-3} carbon doping concentration (low-carbon (LC)) followed by a 15-nm $Al_{0.25}Ga_{0.75}N$ barrier layer. Ohmic contacts were formed by Ti/Al-based metallization defined by means of a liftoff process [11].

Temperature-dependent transient backgating measurements were performed on the ungated structure in order to identify trap levels within the GaN buffer layer [12], [13]. In fact, the tested structure has the benefit that the occupancy of trap levels located at the AlGaN/GaN interface, AlGaN barrier, and device surface will not change because of the 2DEG shielding effect as long as the applied source and drain potentials remain constant and the 2DEG is formed, i.e., ON-state conditions. As a consequence, the tested structure, during current transient backgating measurements, will be sensitive to occupancy variation only of trap levels located within the GaN buffer layers as long as the 2DEG is not fully depleted.

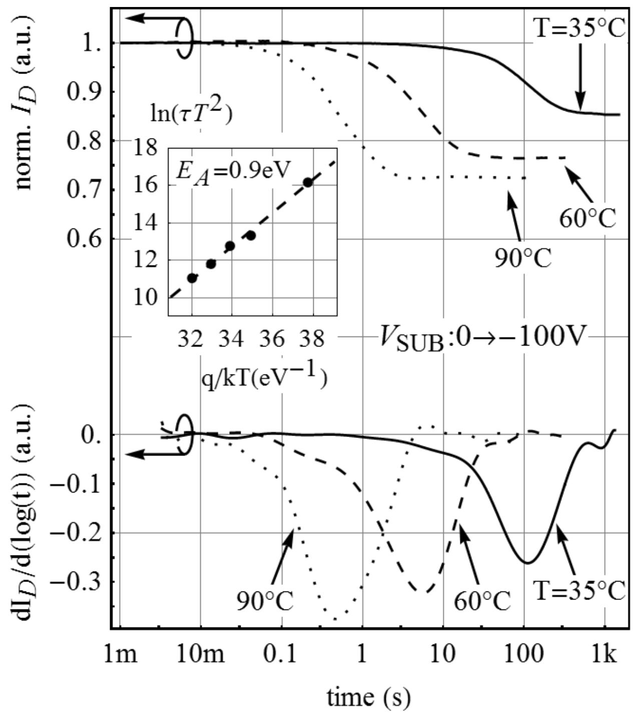

Fig. 2. Recorded normalized drain current transients at $V_{DS} = 0.1$ V obtained when applying a negative voltage step from 0 to −100 V to the wafer backside. Increasing the temperature yields a speedup of the current transient observed, suggesting that the observed phenomena might be related to a thermally activated process. Analysis of the $dI_D/d(\log(t))$ signals showed clear peaks used for the extraction of the time constants τ. Inset: Arrhenius plot obtained which yielded an activation energy $E_A = 0.9$ eV.

The time-dependent drain current I_D, recorded after switching the substrate bias V_{SUB} from 0 to −100 V at the time $t = 0$ s, was measured at $V_{DS} = 0.1$ V (with the source grounded) in order to reduce self-heating effects. The said measurements were performed at temperatures within the range of 35 °C–90 °C. Measured I_D values were then normalized with respect to the measured I_D at 1 ms from the beginning of the transient.

The normalized transients of I_D measured at $T = 35$ °C, 60 °C, and 90 °C are shown in Fig. 2. At $T = 35$ °C, I_D experienced a decrease of approximately 15% with an associated time constant of 100 s. Increasing the temperature induced a speedup in the current-transient suggesting that the observed phenomena might be related to a thermally activated process. Clear peaks were also observed when analyzing the $dI_D/d(\log(t))$ signals (see Fig. 2) related to the transients evaluated at different temperatures. The said signals were then analyzed in order to extract the emission time constants τ [14] of the thermally activated process causing the observed current decrease. If at this point, we suppose that the thermally activated process corresponds to the emission of electrons from a trap level located at $E_C - E_A$ [where E_C is the conduction band (CB) energy and E_A is the activation energy of the trap], or alternatively the emission of holes from a trap level located at $E_V + E_A$ (where E_V is the VB energy), the energy E_A can be extracted as the slope of the Arrhenius plot of $\ln(\tau T^2)$ versus $q/(kT)$, where τ represents the time constant measured at the temperature T, q is the electron charge, and k is the Boltzmann constant. As shown in Fig. 2 (inset), the extracted value of E_A was 0.9 eV.

The 0.9 eV number obtained in this paper well correlates with the 0.86 eV experimental data presented in [9], which has been obtained in similar measurement conditions, i.e., monitoring drain current decrease when applying negative V_{SUB} voltages although the value of V_{SUB} in [9] was −25 V, while in this paper, it was −100 V. We might speculate that the mechanism observed in our devices could be similar to that observed in [9] for $V_{\mathrm{SUB}} = -25$ V. Nevertheless, our interpretation of the physical mechanism leading to the observed drain current decrease is different from that proposed in [9]. As it will be demonstrated in sections IV and V by means of numerical simulations, our proposed explanation relies on a hole-emission process from a carbon-related acceptor-like trap, which is different from the hole conduction mechanism proposed in [9].

When comparing our extracted 0.9-eV activation energy with the 0.93 eV experimental data presented in [10], these two numbers cannot be directly correlated, since the 0.93 eV has been obtained in different conditions, i.e., by monitoring an R_{DSon} recovery, i.e., a drain current increase, by applying $V_{\mathrm{SUB}} = 0$ V after a 100-s stress condition at $V_{\mathrm{SUB}} = -100$ V. As a consequence, the data reported in [10] and that reported in this paper cannot be properly compared, since the activation energy in [10] has been derived from a completely different measurement method where other physical mechanisms than those occurring in the devices tested in this paper might be present.

Before moving to Section III, we would like to briefly comment on the meaning of the activation energy extracted from the Arrhenius plot. The value extracted from the Arrhenius plot itself is not able to distinguish between a hole or an electron trap. The E_A value extracted is related to the distance of the trap level from the CB edge in the case of an electron trap or from the VB edge in the case of a hole trap. Nevertheless, some speculations can be made on the experimental data obtained to understand if the trap causing them is an electron-trap or a hole-trap one. We would like to stress, however, that in order to prove the said speculations, numerical simulations need to be performed, as it is shown in Sections III and IV. Drain current decreases with time, meaning that the number of electrons in the 2DEG decreases as a consequence of the charge variation induced by the trap emission process. As a consequence, only hole emission, i.e., a loss of positive charges in the buffer or equivalently the build-up of a negative charge in the buffer, is consistent with the observed phenomena.

III. Numerical Simulations

In order to gain insights into the physical mechanisms leading to the observed current decrease after applying a negative substrate voltage step, numerical simulations were carried out with the commercial software DESSIS-ISE. For all the simulations, an n-type GaN background doping with a 10^{16} cm^{-3} concentration was adopted, while three different trap configuration scenarios were considered for the LC and HC GaN layers (see Fig. 3). The said scenarios will now be described in detail in Sections III-A–III-C.

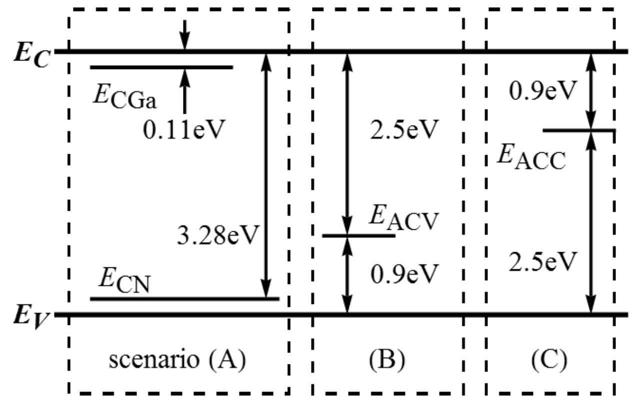

Fig. 3. Three possible trap scenarios were considered for reproducing the experimental results by means of numerical simulations. Scenarios A and B refer to two of the possible compensation mechanisms induced by carbon doping in GaN layers. In particular, Scenario A represents the autocompensation through interplay of $C_N - C_{\mathrm{Ga}}$ states, while Scenario B represents the compensation through a dominant C_N acceptor state. On the other hand, Scenario C is not related in principle to known carbon-doping-related compensation mechanisms, but it has been considered due to the experimentally extracted 0.9-eV activation energy of the thermally activated drain current transient decrease.

A. Trap Scenario A

Scenario A refers to one of the possible compensation mechanisms induced by carbon doping, which predicts the autocompensation through interplay of C_N–C_{Ga} states incorporated during growth with comparable concentration [3], [15]. According to this model, the Fermi level is predicted to be pinned at around midgap, thus making the C-doped buffer to behave as an almost ideal SI layer.

For simulating the effects of this trap configuration, a donor-like trap was introduced at $E_{\mathrm{CGa}} = 0.11$ eV from the CB together with an acceptor-like trap E_{CN} at 3.28 eV from the GaN CB. Trap densities were set according to the carbon doping levels simply by equally splitting them within the two levels, i.e., for the 3×10^{18} cm^{-3} HC layer, 1.5×10^{18} cm^{-3} traps were assigned to the level at E_{CGa} and the remaining 1.5×10^{18} cm^{-3} traps were assigned to the level at E_{CN}.

B. Trap Scenario B

Trap Scenario B refers to the compensating mechanisms induced by dominant C_N acceptor states [16]–[18]. In particular, as reported in [18], using hybrid density functional calculations, it has been shown that carbon on the nitrogen site is in fact a deep acceptor. Calculations reported in [18] and [19] also yielded a (0/−) charge-state transition level $E = 0.9$–1.1 eV above the VB. According to the dominant C_N acceptor states model, the Fermi level will result to be pulled

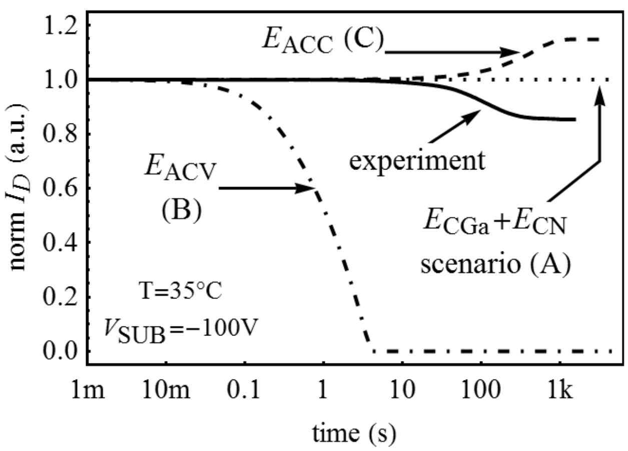

Fig. 4. Comparison among the experimental and simulated normalized drain current transients at $T = 35$ °C when applying a negative voltage step from 0 to -100 V to the substrate: experimental results (solid line), simulated considering Scenario A (dotted line), simulated considering Scenario B (dashed-dotted line), and simulated considering Scenario C (dashed line). Among the three scenarios considered, only Scenario B, corresponding to a compensation mechanism through a dominant C_N acceptor state at 0.9 eV from the GaN VB, yielded a decrease in the drain current level.

in the bottom half of the bandgap turning the GaN buffer into a weakly p-type region [20].

Simulations adopting this model were carried out by introducing an acceptor-like trap level at $E_{ACV} = 0.9$ eV from the GaN VB, with trap densities set according to the carbon doping levels of the structure.

C. Trap Scenario C

Trap Scenario C, differently from Scenarios A and B, has not been chosen according to expected trapping levels related to carbon doping within the GaN layers. According to the 0.9-eV activation energy experimentally extracted, an acceptor-like trap level was considered at 0.9 eV from the GaN CB.

Simulations adopting this model were carried out by introducing an acceptor-like trap level at $E_{ACC} = 0.9$ eV from CB, with trap densities set according to the structure carbon doping levels.

IV. Simulated Current Transients

Simulated current transients according to the three trap scenarios described in Section III and the experimental results obtained at $T = 35$ °C are shown in Fig. 4. The results obtained for each of the three trap scenarios considered will now be discussed as follows.

A. Scenario A Simulation Results

Scenario A [Fig. 4 (dotted line)] did not exhibit any variation in the drain current versus time. This is expected, since the two E_{CGa} and E_{CN} levels are fully ionized regardless of the applied substrate voltage. As a consequence, the negative charge build-up in the buffer, which is required in order to induce the observed drain current decrease, will never come into place.

B. Scenario B Simulation Results

Scenario B [see Fig. 4 (dashed-dotted line)] yielded a significant decrease in the simulated current level, actually turning OFF completely the 2DEG. Again, the trends are expected, since E_{ACV} will behave as an hole trap, and it will be briefly discussed. When a negative V_{SUB} is applied, the depletion region within the GaN buffer layers will increase its extension. Trapped holes within the said depletion region should then be swept away, although this mechanism will have to follow the timing related to the emission process of the hole traps. As time passes by, holes are emitted, leaving negatively ionized acceptors within the depleted region. A negative charge build-up will thus occur in the buffer, inducing a decrease in the 2DEG density and consequently in the current level with time constant related to the hole emission process.

C. Scenario C Simulation Results

Scenario C [see Fig. 4 (dashed line)] resulted in a complete opposite trend with respect to Scenario B and experimental results, yielding an increase of the current during the simulated transient. The charge dynamic involved during the current increase can be briefly explained as follows. When $V_{SUB} = 0$ V, the traps are filled by electron in the buffer layer in order to compensate the effect of the n-type background doping, resulting in the Fermi level being pinned at 0.9 eV from the CB. As V_{SUB} is pulled to negative values, the depletion region forming within the buffer layer sweeps away the trapped electrons, with time constants related to their emission process, inducing a positive charge build-up in the buffer due to the presence of the background donors that are no longer neutralized by the trapped electrons.

We can thus conclude this preliminary qualitative analysis by stating that among the three model considered, only Scenario B is able to predict the measured current decrease versus time. Hole traps associated with the C_N acceptor states thus seem to be the main responsible of the experimentally observed thermally activated drain current decrease when negative substrate voltage levels are applied to the tested structures.

V. Quantitative Fitting of Experimental Data

As observed in Section IV, among the three different trap scenarios considered, only Scenario B was able to reproduce a drain current decrease versus time.

While this result qualitatively follows the experimental one, simulations are predicting a larger current variation if compared with the measured one. This quantitative discrepancy between the measured ad simulated drain currents suggests that the trap concentrations used in simulation might be larger than those actually involved in the real tested device.

Since we observed that Scenario A yielded no current variation while only Scenario B was yielding a decrease in current level, additional numerical simulations were carried out by adjusting the trap concentration within the simulated structure according to the following method. Naming x as a certain fraction of the nominal carbon doping levels,

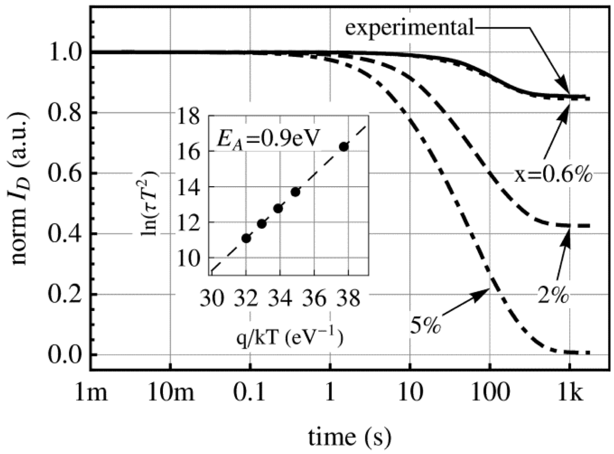

Fig. 5. Simulated normalized drain current transients obtained by varying the fraction x of carbon doping associated with the Scenario B trap level density. A nice fitting of the experimental data (solid line) is obtained by means of numerical simulations when $x = 0.6\%$ (dotted line). Inset: calculated Arrhenius plot obtained by carrying out simulated transients at different temperatures yielding a 0.9-eV activation energy.

i.e., 3×10^{16} cm^{-3} for the LC and 3×10^{18} cm^{-3} for the HC layers, respectively, the number of trap level related to Scenario B was set equal to x, while the remaining $1 - x$ was equally distributed within the shallow-donor and shallow-acceptor trap levels of Scenario A.

As shown in Fig. 5, varying x allowed us to quantitatively reproduce the experimentally recorded transient, which was adequately fitted for an x value equal to 0.6%, i.e., corresponding to a 1.8×10^{16} cm^{-3} E_{ACV} trap concentration in the HC buffer layer. The capture cross section used in the simulations for the E_{ACV} trap level was 1.3×10^{-14} cm^{-2}. The said capture cross section value was chosen in order to match the experimental current transients and to obtain a nice overlap between the experimental [see Fig. 2 (inset)] and simulated [Fig. 5 (inset)] Arrhenius plots. Lower values of the capture cross section leaded to slower transients and vice versa, with 1.3×10^{-14} cm^{-2} being the capture cross section value, which yielded the nice fit with the experimental data reported in Fig. 5. Simulations with $x = 0.6\%$ were also carried out at different temperatures, and by adopting the method based on the $dI_D/d(\log(t))$ signal peak extraction, the Arrhenius plot reported in Fig. 5 (inset) was calculated, yielding a 0.9-eV activation energy.

Some comments are now needed in order to discuss the large discrepancy, approximately two orders of magnitude, between the nominal carbon doping values and those required in order to reproduce the current transients with numerical simulation. A similar difference between the nominal carbon doping and the effective trap density has also been observed in [17] when studying the deep levels in n-GaN carbon-doped layer by means of minority carrier transient spectroscopy measurements. In particular, the signature of a hole trap at 0.86 eV from VB was reported in [17], which is in agreement with our findings, both on low-carbon ($2–5 \times 10^{16}$ cm^{-3}) and high-carbon (1×10^{17} cm^{-3}) doped n-type GaN layers. The extracted trap densities in [17] were also 1.8×10^{14} cm^{-3} and 2.2×10^{15} cm^{-3} for the low-carbon and high-carbon samples, respectively. The increase in trap density with increasing carbon doping clearly correlated the hole trap with the carbon doping in the experiment carried out in [17]. Moreover, similar to our findings, they also observed approximately the two orders of magnitude ratio between the effective carbon doping and the hole-trap concentration. In agreement with our results, photocapacitance and deep-level transient spectroscopy measurements reported in [21] also demonstrated that less than 2% of the nominal carbon concentration created traps at a 0.9 eV level from the GaN VB. Concerning the remaining part of the carbon doping, it was reported in [21] that 15%–20% is related to different levels and the other part, about 80%, is still not allocated.

This result further supports our findings based on the quantitative fitting of the experimental data, where only 0.6% of the carbon doping participates to the depletion of the 2DEG.

VI. Conclusion

To the best our knowledge, we have provided, for the first time, a clear and quantitative explanation of drain current decrease transients induced by carbon-related buffer traps, which only involves the hole-emission physical process related to an acceptor trap located at 0.9 eV from the GaN VB, which is one of the known levels forming within C-doped GaN layers [16]–[18].

The current reduction in the tested ungated AlGaN/GaN structures during backgating transient measurements is related to a hole-emission process from an acceptor-like hole-trap level with a density corresponding to 0.6% of the nominal carbon doping concentration.

Both the trap energy as well as the ratio between the trap density and the nominal carbon doping are also in agreement with the previous findings obtained by means of different measurement techniques, with respect to that adopted in this paper, on C-doped GaN layers [17], [21].

The results proposed in this paper can potentially provide insights into the physical mechanisms involved also in the performance degradation of GaN-based HEMTs grown on C-doped buffers. The measurement conditions used here on ungated structures will correspond, in first approximation, to those experienced by HEMT devices in their gate–drain access region when large positive drain voltage is applied in the OFF-state conditions with their substrate grounded. As a consequence, the trap configuration scenario that fitted the experimental results could be used to predict and/or investigate the performance degradation in GaN-based HEMTs with C-doped GaN buffer layers.

References

[1] R. Mitova, R. Ghosh, U. Mhaskar, D. Klikic, M.-X. Wang, and A. Dentella, "Investigations of 600-V GaN HEMT and GaN diode for power converter applications," *IEEE Trans. Power Electron.*, vol. 29, no. 5, pp. 2441–2452, May 2014.

[2] Y.-F. Wu, J. Gritters, L. Shen, R. P. Smith, and B. Swenson, "kV-Class GaN-on-Si HEMTs enabling 99% efficiency converter at 800 V and 100 kHz," *IEEE Trans. Power Electron.*, vol. 29, no. 6, pp. 2634–2637, Jun. 2014.

[3] A. Armstrong, C. Poblenz, D. S. Green, U. K. Mishra, J. S. Speck, and S. A. Ringel, "Impact of substrate temperature on the incorporation of carbon-related defects and mechanism for semi-insulating behavior in GaN grown by molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 88, no. 8, pp. 082111–082114, Feb. 2006.

[4] E. Bahat-Treidel, F. Brunner, O. Hilt, E. Cho, J. Wurfl, and G. Trankle, "AlGaN/GaN/GaN:C back-barrier HFETs with breakdown voltage of over 1 kV and low $R_{ON} \times A$," *IEEE Trans. Electron Devices*, vol. 57, no. 11, pp. 3050–3058, Nov. 2010.

[5] J. Würfl *et al.*, "Techniques towards GaN power transistors with improved high voltage dynamic switching properties," in *Proc. IEEE Int. Electron Devices Meeting (IEDM)*, Dec. 2013, pp. 6.1.1–6.1.4.

[6] P. Moens *et al.*, "On the impact of carbon-doping on the dynamic Ron and off-state leakage current of 650 V GaN power devices," in *Proc. IEEE 27th Int. Symp. Power Semiconductor Devices ICs (ISPSD)*, May 2015, pp. 37–40.

[7] M. J. Uren, J. Möreke, and M. Kuball, "Buffer design to minimize current collapse in GaN/AlGaN HFETs," *IEEE Trans. Electron Devices*, vol. 59, no. 12, pp. 3327–3333, Dec. 2012.

[8] J. A. Croon, G. A. M. Hurkx, J. J. T. M. Donkers, and J. Šonský, "Impact of the backside potential on the current collapse of GaN SBDs and HEMTs," in *Proc. IEEE 27th Int. Symp. Power Semiconductor Devices ICs (ISPSD)*, May 2015, pp. 365–368.

[9] M. J. Uren, M. Cäsar, M. A. Gajda, and M. Kuball, "Buffer transport mechanisms in intentionally carbon doped GaN heterojunction field effect transistors," *Appl. Phys. Lett.*, vol. 104, no. 26, pp. 263505-1–263505-4, Jun. 2014.

[10] G. Meneghesso, M. Meneghini, R. Silvestri, P. Vanmeerbeek, P. Moens, and E. Zanoni, "High voltage trapping effects in GaN-based metal–insulator–semiconductor transistors," *Jpn. J. Appl. Phys.*, vol. 55, no. 1S, pp. 01AD04-1–01AD04-5, Jan. 2016.

[11] F. Iucolano, G. Greco, and F. Roccaforte, "Correlation between microstructure and temperature dependent electrical behavior of annealed Ti/Al/Ni/Au Ohmic contacts to AlGaN/GaN heterostructures," *Appl. Phys. Lett.*, vol. 103, no. 20, pp. 201604-1–201604-4, Nov. 2013.

[12] M. Marso, M. Wolter, P. Javorka, P. Kordoš, and 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.*, vol. 82, no. 4, pp. 633–635, Jan. 2003.

[13] C. Zhou, Q. Jiang, S. Huang, and K. J. Chen, "Vertical leakage/breakdown mechanisms in AlGaN/GaN-on-Si devices," *IEEE Electron Device Lett.*, vol. 33, no. 8, pp. 1132–1134, Aug. 2012.

[14] M. Ťapajna, R. J. T. Simms, Y. Pei, U. K. Mishra, and M. Kuball, "Integrated optical and electrical analysis: Identifying location and properties of traps in AlGaN/GaN HEMTs during electrical stress," *IEEE Electron Device Lett.*, vol. 31, no. 7, pp. 662–664, Jul. 2010.

[15] A. F. Wright, "Substitutional and interstitial carbon in wurtzite GaN," *J. Appl. Phys.*, vol. 92, no. 5, pp. 2575–2585, Sep. 2002.

[16] A. Armstrong, A. R. Arehart, D. Green, U. K. Mishra, J. S. Speck, and S. A. Ringel, "Impact of deep levels on the electrical conductivity and luminescence of gallium nitride codoped with carbon and silicon," *J. Appl. Phys.*, vol. 98, no. 5, pp. 053704-1–053704-11, Sep. 2005.

[17] U. Honda, Y. Yamada, Y. Tokuda, and K. Shiojima, "Deep levels in n-GaN doped with carbon studied by deep level and minority carrier transient spectroscopies," *Jpn. J. Appl. Phys.*, vol. 51, no. 4S, pp. 04DF04-1–04DF04-4, Apr. 2012.

[18] J. L. Lyons, A. Janotti, and C. G. Van de Walle, "Carbon impurities and the yellow luminescence in GaN," *Appl. Phys. Lett.*, vol. 97, no. 15, pp. 152108-1–152108-3, Oct. 2010.

[19] D. O. Demchenko, I. C. Diallo, and M. A. Reshchikov, "Yellow luminescence of gallium nitride generated by carbon defect complexes," *Phys. Rev. Lett.*, vol. 110, no. 8, pp. 087404-1–087404-5, Feb. 2013.

[20] M. J. Uren *et al.*, "Intentionally carbon-doped AlGaN/GaN HEMTs: Necessity for vertical leakage paths," *IEEE Electron Device Lett.*, vol. 35, no. 3, pp. 327–329, Mar. 2014.

[21] T. Tanaka, K. Shiojima, Y. Otoki, and Y. Tokuda, "A study on multiple defect states in low-carbon doped GaN layers and its correlation with AlGaN/GaN high electron mobility transistor operation," *Thin Solid Films*, vol. 557, pp. 207–211, Apr. 2014.

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