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On the dynamic R_{ON}, vertical leakage and capacitance behavior in pGaN HEMTs with heavily carbon-doped buffers

Marcello Cioni, Alessandro Chini, Nicolò Zagni, *Member, IEEE,* Giovanni Verzellesi, *Senior Member, IEEE*, Giovanni Giorgino, Giacomo Cappellini, Cristina Miccoli, Gaetan Toulon, Tariq Wakrim, Maria Eloisa Castagna, Aurore Constant and Ferdinando Iucolano

***Abstract*— In this letter, we investigate the effect of Carbon (C) doping concentration on dynamic R_{ON}, vertical leakage and Capacitance-Voltage (C-V) characteristics of p-GaN gate High Electron Mobility Transistors (HEMTs). Measurements performed on state-of-the-art samples show that further increasing C-doping concentration in the GaN buffer above 10^{19} cm^{-3} yields a reduced dynamic-R_{ON} degradation, in contrast with the behavior reported in the literature for lower C-doping concentrations. This is confirmed by a complete data set showing a consistent increase in the vertical leakage and in the output capacitance while increasing the C doping, stemming from a less insulating buffer and a reduced 2-DEG depletion, respectively. These observations can be attributed to an increased incorporation of compensating donors leading to a reduction of the net acceptors as the C doping concentration is raised above 10^{19} cm^{-3}.**

***Index Terms*—p-GaN HEMTs, Dynamic R_{ON}, C-doping, Compensation Ratio, Output Capacitance.**

I. INTRODUCTION

CARBON impurities incorporation during growth of the buffer layer of GaN-based devices is a critical process that influences several figures of merit such as dynamic R_{ON}, off-state leakage current (I_{OFF}), breakdown voltage (V_{BR}), etc. [1], [2]. Specifically, C-dopants decrease the buffer layer conductivity, thus reducing I_{OFF} and increasing V_{BR}. The trade-off is the increased dynamic R_{ON} [2]–[4] due to the dynamics of charging/discharging of traps associated with carbon [5]–[7].

Typically, C incorporation in undoped GaN layers used as buffer in high electron mobility transistors (HEMTs), leads to the formation of C_N sites (i.e., C substitutes N atoms) which behave predominantly as deep acceptors [8] while it also leads to the formation of C_{Ga} sites (i.e., C substitutes Ga atoms), which act instead as shallow donors [9]. These donors partially compensate the acceptors and thus affect both buffer conductivity (and in turn I_{OFF}, V_{BR}) [10] and dynamic R_{ON} [11]. Therefore, it is the effective C-related trap concentration (i.e., $N_{C,EFF} = N_{C,A}–N_{C,D}$) or equivalently the compensation ratio (CR $= N_{C,D}/N_{C,A}$) that determines the electrical behavior of the device. Previous reports have shown that both V_{BR} [3], [12] and dynamic R_{ON} [3] increase with increasing C concentration, consistently with the assumption of higher incorporation of acceptor traps [11]. However, in [12, 13] it has been shown that further increase of C concentration above ≈10^{19} cm^{-3} leads to a saturation of V_{BR}, while in [14] V_{BR} was found to decrease. Nevertheless, the dynamic R_{ON} or other electrical parameter behavior at very high C concentration, have not been presented so far.

In this letter, we present a comprehensive set of results collected on p-GaN HEMTs with three different C-doping concentrations showing how vertical breakdown and dynamic R_{ON} both decrease with increasing C concentration above ≈10^{19} cm^{-3}, while the output capacitance increases in the same C-doping range. These results are attributed to the increasing degree of acceptors compensation by donor traps as further C impurities are incorporated in the buffer.

II. DEVICE CHARACTERIZATION

Devices under test (DUT's) are 650-V p-GaN power HEMTs with Schottky gate contact, grown on Silicon substrate. The structure of the DUTs as well as more details regarding the epitaxy can be found in [7]. The GaN buffer is Carbon doped to obtain a semi-insulating layer [4] and three epitaxies with different C doping concentrations in the buffer are considered, namely Buffer A, Buffer B and Buffer C, with $[C]_A<[C]_B<[C]_C$. The different Carbon doping levels were achieved through extrinsic C-doping via C_2H_4 precursor. In particular, the C-doping profiles extracted by Secondary Ion Mass Spectroscopy

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M. Cioni, G. Giorgino, G. Cappellini, C. Miccoli, M. E. Castagna and F. Iucolano are with STMicroelectronics, 95121, Catania, Italy. (*Corresponding author*: M. Cioni. E-mail: marcello.cioni@st.com).

G. Toulon is with STMicroelectronics, 31670, Toulouse, Italy.

A. Constant and T. Wakrim are with STMicroelectronics, 37071, Tours, France.

A. Chini and N. Zagni are with the Department of Engineering "Enzo Ferrari", Università di Modena e Reggio Emilia, 41125, Modena, Italy.

G. Verzellesi is with Department of Sciences and Methods for Engineering (DISMI) and EN&TECH Center, University of Modena and Reggio Emilia, 42122, Reggio Emilia, Italy.

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TABLE I
DEVICES PARAMETERS COMPARISON

Parameter (@ 25°C)	Buffer A $[C]_A$	Buffer B $[C]_B$	Buffer C $[C]_C$
2DEG	6.8 x 10^{12} cm^{-2}	6.8 x 10^{12} cm^{-2}	6.6 x 10^{12} cm^{-2}
e Mobility	1700 cm^2/Vs	1718 cm^2/Vs	1730 cm^2/Vs
g_m peak	94 mS/mm	96 mS/mm	98 mS/mm
R_C	0.4 Ωxmm	0.4 Ωxmm	0.4 Ωxmm
$I_{D,SAT}$	242 mA/mm	251 mA/mm	254 mA/mm
V_{BR}	>1000 V	>1000 V	>1000 V

g_m peak: peak of transconductance in saturation region. R_C: contact resistance, $I_{D,SAT}$: saturation current, V_{BR}: breakdown voltage.

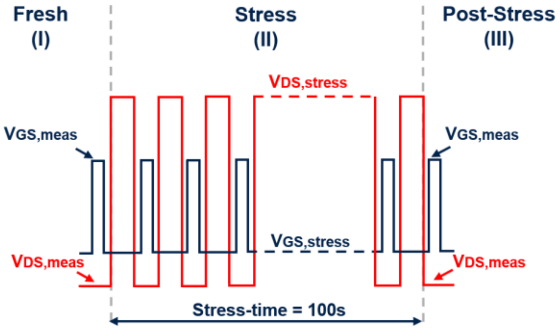

Fig. 1: Stress/Measurement sequence implemented with the AM200 Pulsed I-V equipment for dynamic-R_{ON} characterization. The Fresh_R_{ON} (I) is first acquired with ($V_{GS,meas}$; $V_{DS,meas}$)=(6 V; 1 V); then the stress (II) is performed at ($V_{GS,stress}$; $V_{DS,stress}$) = (0 V; 400 V) with 50 kHz switching frequency and DC=25% for a total cumulative stress-time of 100 s at T=100 °C. (III) The post-stress R_{ON} is extracted and the dynamic R_{ON}-degradation is computed as the ratio (R_{ON}-Fresh_R_{ON})/Fresh_R_{ON} expressed in percentage.

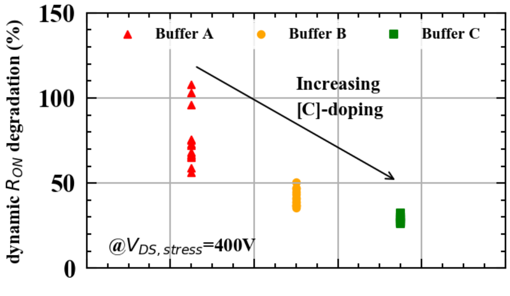

Fig. 2. Dynamic R_{ON} (%) measured after 100s stress at $V_{DS,stress}$=400 V, T=100 °C on samples showing three different C-doping concentrations in the GaN buffer layer (Buffer A, Buffer B, Buffer C). R_{ON}-degradation decreases while increasing the C-doping concentration. To verify the results repeatability, 15 devices have been tested for each buffer type.

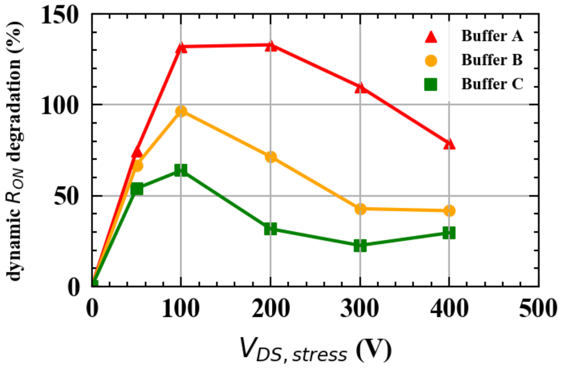

Fig. 3. Dynamic R_{ON} degradation(%) measured after 100s stress at T=100 °C for different $V_{DS,stress}$ values in the 0V to 400V voltage range. The trend observed at 400 V is confirmed in the whole voltage range considered, indicating a reduced net acceptor concentration in the Buffer while increasing the C-doping concentration ($[C]_A < [C]_B < [C]_C$).

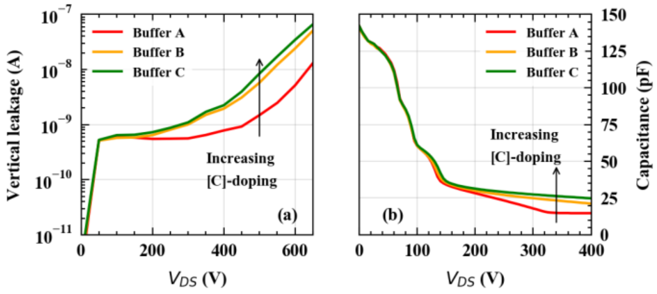

Fig. 4. (a) Vertical leakage current measured at T=25 °C on the DUTs showing different C-doping concentration. The vertical leakage increases while increasing the C-doping level, stemming for a less insulating buffer (i.e., reduced net acceptor concentration). (b) Capacitance-Voltage (C_{OSS}-V) measurement in off-state performed on the three buffer types (A, B and C) with 1 MHz frequency. At relatively high voltage (e.g., 400 V) the output capacitance increases while increasing the C-doping, stemming for a reduced 2-DEG depletion (i.e., reduced negative charge exposed in the Buffer).

(SIMS) revealed a $[C]_A$>1x10^{19} cm^{-3} and $[C]_C$<8x10^{19} cm^{-3}. In Table I, we reported some key parameters measured on the three buffer types considered. This comparison shows that totally similar samples, apart from the C-doping level in the Buffer, are compared in this study. To investigate the dynamic-R_{ON} of the three samples, a stress/measurement sequence mimicking operating switching conditions is considered as shown in Fig. 1. The DUTs are continuously switched between off-state ($V_{GS,stress}$; $V_{DS,stress}$) and on-state ($V_{GS,meas}$; $V_{DS,meas}$) under soft-switching conditions. Prior to stress, the static R_{ON} is acquired to set a reference fresh value for this parameter (R_{ON0}) while the post-stress R_{ON} is evaluated after 100 s of cumulative stress time, to induce a steady state R_{ON}-degradation on the DUTs.

III. RESULTS

The stress/measurment sequence described in Section II is used to characterize the three type of DUTs considered. The first condition explored is the one related to a typical voltage rating used for 650-V GaN switches, i.e., $V_{DS,stress}$=400 V. The R_{ON}-degradation (R_{ON}/R_{ON0} in percentage) obtained on Buffer A, B and C samples is reported in Fig. 2. As it can be observed, the R_{ON}-degradation decreases while increasing C concentration in the buffer, contrary to what previously observed in the literature in samples with lower C concentration, for which dynamic R_{ON} increased with C doping [3]. There are two possible explanations for the observed trend:
(i) an increase of the peak electric field located near the drain contact, yielding a stronger recovery of dynamic-R_{ON} that typically shows up at high $V_{DS,stress}$ [7];
(ii) an increased incorporation of C_{Ga} compensating donors in the GaN buffer [9] leading to a CR increase [8] and thus to a decreased net acceptor concentration, in turn reducing dynamic R_{ON}. Additionally, if (ii) is the case, then dynamic R_{ON} reduction with increasing C concentration should be observed

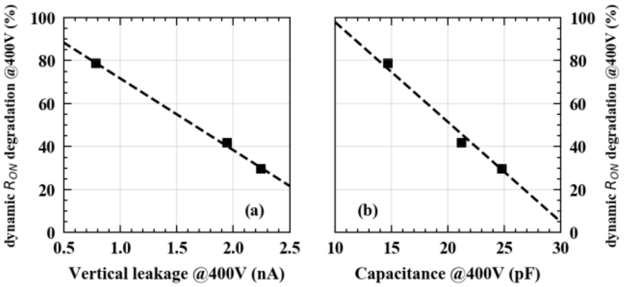

Fig. 5. (a) Correlation between Vertical leakage and dynamic R_{ON} degradation measured at $V_{DS,stress}$=400 V. Higher Leakage (i.e., reduced buffer isolation) corresponds to lower dynamic R_{ON} coherently with a reduced net acceptor concentration in the Buffer layer.(b) Correlation between Capacitance and dynamic R_{ON} measured at $V_{DS,stress}$=400 V. Higher Capacitance corresponds to lower dynamic R_{ON} coherently with a reduced net acceptor concentration in the buffer layer (i.e., reduced 2-DEG depletion).

in the whole voltage range and not only at high $V_{DS,stress}$ (partial recovery in fact does not occur for $V_{DS,stress}$<≈100 V).

To verify this, we performed the same characterization on the three samples for $V_{DS,stress}$ in the 50 V to 400 V range, obtaining the results shown in Fig. 3. Figure 3 clearly shows that coherently with (ii), the dynamic R_{ON} decreases in the whole voltage range explored even below ≈100 V, thus ruling out case (i) as possible explanation for the results. Actually, partial dynamic R_{ON} recovery (e.g., difference between dyn-R_{ON}@100 V and dyn-R_{ON}@400 V) was found to decrease with increasing C concentration, further confirming the validity of hypothesis (ii). Accordingly, the experimental results show that the net acceptor concentration (responsible for dynamic R_{ON} on C-doped GaN samples) decreases while increasing the C doping above 10^{19} cm^{-3}. This is actually possible if CR increases, thus incorporating more donor states (C_{Ga}) that compensate C_N acceptors. This implies a non-constant CR with increasing C doping, that is rather likely by considering that CR could be significantly affected by the epitaxial growth condition and Fermi level position [15, 16]. Another effect concurrently taking place with increasing C concentration is the one reported in [13], i.e., the presence of threading dislocations that, by gettering C impurities, could reduce the net acceptor concentration in the buffer.

To further support the interpretation, we performed vertical leakage (I_{SUB}-V_D) and output capacitance-voltage (C_{OSS}-V_D) measurements, the results of which are shown in Fig. 4. Both measurements reported in Fig. 4 are coherent with the proposed interpretation. As a matter of fact, vertical leakage increases with increasing C doping, see Fig. 4(a), which is signature of a less insulating buffer as a result of the reduced net acceptor concentration. On the other hand, the output capacitance increases with increasing C concentration, see Fig. 4(b),which stems from a reduced depletion of the 2-DEG again due to the reduced negative charge in the buffer. As a matter of fact, at increasing drain voltage the device experiences a progressive extension of the depletion region toward the drain contact leading to 2DEG depletion. In particular, for the voltage range between 0 V and 150 V (on tested devices) we observed a progressive depletion of the 2DEG under the Source Field-Plates as well as a modulation of the Capacitance-Voltage curve due to the different pinch-off voltages of the Field-Plates. At higher voltages, 2DEG depletion in the gate-drain access region leads to the modulation of the high voltage capacitance (determined by the 2DEG residual charge). Accordingly, different high voltage capacitance values correspond to different residual 2DEG charges in the gate-drain access region. The residual charge in the 2DEG is modulated by the net negative charge in the buffer due to the ionization of the net Carbon acceptors. Accordingly, the samples showing higher R_{ON} degradation (e.g., sample A) are characterized by a larger 2DEG depletion in this voltage range. This yields a lower residual charge in the gate-drain access region which yields a faster roll-off of the high voltage capacitance. This was already observed in [17], in which C-V obtained by TCAD simulations showed the critical role played by C_{Ga} donors in determining the high voltage capacitance (corresponding to the residual 2-DEG concentration in the access region under OFF-state conditions). However, this is the first time in which this interpretation is supported by experimental data on samples with different C-doping levels.

Summarizing, all the experimental data shown so far are consistent with the interpretation that, above a certain C concentration, the increasing incorporation of compensating donors in the GaN buffer decreases the net acceptor concentration, yielding a less insulating layer and a reduced net negative charge. This explains the correlation between dynamic R_{ON} reduction, leakage current increase and the high-voltage output capacitance increase as shown in Fig. 5. This correlation supports the physical interpretation and provides two alternative experiments (I-V and C-V) that can be used to evaluate the buffer properties before performing dynamic-R_{ON} characterization.

IV. CONCLUSIONS

In this letter, we investigated the effect of Carbon doping concentration in the GaN buffer on dynamic-R_{ON}, drain leakage current and output capacitance of p-GaN gate AlGaN/GaN HEMTs. A comprehensive data set of DC, AC and pulsed measurements was used to understand the non-trivial dependence of the above electrical quantities on C-doping concentration above 10^{19} cm^{-3}. Specifically, it was found that increasing C concentration above 10^{19} cm^{-3} yields a reduced dynamic-R_{ON}, increased leakage current and high voltage output capacitance. All these results can be attributed to a reduced net acceptor concentration in the buffer. The correlation between different electrical parameters presented in this letter points out that, while a reduced net acceptor concentration in the buffer reduces dynamic-R_{ON} and thus decreases conduction losses in power-converter applications, the concurrent increase in leakage current and high-voltage output capacitance is an issue in terms of device reliability and switching losses, respectively. Therefore, the choice of the optimum C-doping concentration of the GaN buffer layer leads to critical design considerations to find the best trade-off in terms of dynamic R_{ON}, leakage current and high-voltage output capacitance.

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