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# Inspection of Trapping and Detrapping Dynamics in Fe- and C-doped GaN-based RF HEMTs by Filling Pulse-Dependent DCT Spectroscopy

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## Abstract

The variations in the emission time constant and drain current transient (DCT) amplitude of traps in Fe- and C-doped HEMTs are analyzed at different trap-filling biases and pulse widths. Accordingly, the electron capture and emission dynamics of trap at  $E_C - 0.57$  eV in the Fe-doped InAlGa<sub>N</sub>/Ga<sub>N</sub> HEMT are reported. Relatively longer emission time constants ( $> 100$  s at 30 °C) are identified for the trap at  $E_C - 0.33$  eV in the C-doped AlN/GaN HEMTs.

Keywords: GaN HEMT, Trap, and Current transient.

## Introduction

Gallium nitride (GaN)-based high-electron mobility transistors (HEMTs) are being employed in microwave monolithic integrated circuits (MMICs) and RF power amplifiers. The compensational dopant (Fe or C) introduction in the buffer layer is an inevitable process in the GaN HEMT technology, as it is beneficial in mitigating vertical leakage, increasing breakdown voltage, and confining 2DEG density. Nonetheless, the electron trapping in the buffer dynamically decreases the drain current (current collapse), increases the on-resistance, and induces DC-RF current dispersions. As a result, the dynamic reduction in the RF output power and efficiency is expected under pulsed operation due to the trapping effects. The large signal operation of the RF transistor covers the entire safe operating area (almost all DC zones), so it is important to understand the charge trapping and detrapping kinetics at various bias points, such as OFF-, deep-OFF-, ON-, and semi-ON states. Accordingly, electron capture and emission processes in the Fe- and C-doped HEMTs are evaluated under different trap-filling bias conditions by drain current transient (DCT) spectroscopy experiments. The class AB operation of the GaN-based amplifiers typically lies at a semi-ON bias voltage. For this reason, the detrapping transients are measured at the semi-ON bias point. Furthermore, variations in the emission time constant ( $\tau_n$ ) and DCT amplitude ( $\Delta I_{DS}$  variation depends on the ionized buffer density profile) of the traps are inspected with increasing pulse widths.

The trap-filling pulse dependency on  $\tau_n$  and  $\Delta I_{DS}$  of the Fe-related traps in the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT were reported by Bisi *et al.* [1], Meneghini *et al.* [2], and Zagni *et al.* [3]. Nevertheless, the carrier capture and emission dynamics of the Fe-related traps are not well understood till now. Recently,

Angelotti *et al.* [4] carried out systematic DCT characterization studies to examine the charge trapping kinetics in double-heterojunction AlN/GaN/AlGa<sub>N</sub> HEMT, but their device structure did not contain the GaN buffer layer. The C-related buffer trapping effects are rather complex to understand, and the associated studies could be sparser in the literature, than the Fe-doped HEMTs. In this work, the DCT measurements are carried out in two HEMT devices with different buffer doping technologies: Fe-doped InAlGa<sub>N</sub>/Ga<sub>N</sub> HEMT and C-doped AlN/GaN HEMT. This work is attempted to understand the trapping and detrapping in the 100 nm HEMTs under different pulsing conditions.

## Experiment

The InAlGa<sub>N</sub>/Ga<sub>N</sub> and AlN/GaN HEMT structures were grown on a semi-insulating silicon carbide substrate. The Fe-doping is intentionally introduced in the GaN buffer region of the InAlGa<sub>N</sub>/Ga<sub>N</sub> heterostructure. The GaN buffer layer of the AlN/GaN structure is doped with the compensational C-impurity. The InAlGa<sub>N</sub>/Ga<sub>N</sub> and AlN/GaN HEMTs feature 0.1  $\mu\text{m}$  gate length, 50  $\mu\text{m}$  gate width with six fingers (gate size of 6 $\times$ 50  $\mu\text{m}$ ), and silicon nitride passivation. Further details of the epilayer and device structure cannot be provided to protect the intellectual property rights.

The DCT measurement setup is described elsewhere [5]. The energy and capture cross-section of the traps were already identified by temperature dependent DCT spectroscopy, hence they are not presented here. The trap-filling in the Fe-doped HEMT was achieved by pulsing the device terminal voltages into three different quiescent bias points ( $V_{GF}$ ,  $V_{DF}$ ): semi-ON state (-1.6 V, 15 V), OFF-state (-7 V, 0 V), and deep-OFF-state (-7 V, 12 V). Subsequently, the emission transients were measured at a semi-ON bias voltage ( $V_{GM}$ ,  $V_{DM}$ ) = (-1.6 V, 5 V), as it closely resembles the class AB operation bias of the GaN amplifier. The low drain voltage ( $\leq 5$  V) was selected to reduce the self-heating effect on the electron emission transients. In the first quiescent bias case, the voltage pulsing was done only at the drain terminal, i.e., single-pulsed drain-lag DCT spectroscopy. The drain and gate voltages were simultaneously pulsed in the other two cases (double-pulsed DCT). At a fixed temperature of 30 °C, the DCT spectrum was measured by varying the filling-pulse width from 1  $\mu\text{s}$  to 100 s (at 9 different pulse durations). The traps in C-doped HEMT were populated at two quiescent bias points ( $V_{GF}$ ,  $V_{DF}$ ): OFF-state (-6 V, 0 V), and deep-OFF-state

(-6 V, 10 V); consequently, the DCT emission transient was measured at a semi-ON bias ( $V_{GM}, V_{DM}$ ) = (-0.37 V, 2 V).

## Results and Discussion

The threshold voltage of InAlGaN/GaN and AlN/GaN HEMTs is -3 V, and -0.8 V, respectively. The temperature-dependent DCT reveals an electron trap at  $E_C - 0.57$  eV (F1) in Fe-doped InAlGaN/GaN HEMT and a trap at  $E_C - 0.33$  eV (C1) in C-doped AlN/GaN HEMT (not shown here). The filling-pulse dependencies of these traps are described below.

### A. Fe-doped 0.1 $\mu\text{m}$ InAlGaN/GaN HEMT

Figs. 1(a) and (b) show the drain-lag DCT and its derivative spectra attained with different filling-pulse widths ( $t_{fill}$ ) ranging from 1  $\mu\text{s}$  to 100 s. However, no significant change in  $\tau_n$  and  $\Delta I_{DS}$  of the trap F1 is noted, similar to our earlier observations in the Fe-doped AlGaIn/GaN HEMTs. Under drain-lag pulsing conditions, highly energetic hot electrons are injected into the gate-drain access region, where they get trapped by the buffer acceptor traps [1], [2]. The filling-pulse-independent drain-lag DCT spectra indicate that the acceptor traps in the gate-drain access region of GaN buffer are fully ionized by hot electrons even at lower  $t_{fill} = 1$   $\mu\text{s}$ .

The double-pulsed DCT spectra acquired upon the OFF-state quiescent bias are depicted in Fig. 2;  $\tau_n$  is found to increase with  $t_{fill}$ . The gate-to-channel leakage current induces considerable electron trapping in the buffer at the sub-threshold gate voltages (-7 V, 0 V) [1], [2]. The trapping process gets augmented with the elapsed time, especially at the drain-side of the gate edge region, where the peak electric field occurs. This implies that the gate leakage current in the OFF-state promotes trapping and accelerates the RF current collapse effects. The buffer traps are supposed to be densely agglomerated at the gate-edge region, and the clustered point defects may split the discrete energy levels into a band of trap energies inside the bandgap [5]. Relative to the point defect states, the defect bands behave quite differently in capturing and emitting electrons, due to the columbic force between the closely located trapped carriers in the disordered regions. So, the observed increase in  $\tau_n$  may be caused by the extended line defects and dislocations in the buffer layer. Another important observation in Fig. 2,  $\Delta I_{DS}$  increases with the pulse width and reaches maximum at  $t_{fill} = 10$  ms (trap-filling saturated at  $t_{fill} = 10$  ms); however, beyond that ( $t_{fill} \geq 100$  ms),  $\Delta I_{DS}$  decreases. The emission time constant of the trap F1 lies in the range of 1 ms to 40 ms at 30  $^\circ\text{C}$ , as seen in Figs. 1-2. Once the filling pulse duration exceeds the characteristic  $\tau_n$  of the trap at a specific temperature ( $t_{fill} > \tau_n$ ), partial electron emission is possible even during the capture transient due to the lengthier time window [1], as realized in Fig. 2.

The double-pulsed DCT spectra obtained upon the deep-OFF-state quiescent bias stress are plotted in Fig. 3. At deep negative  $V_{GF}$  and high  $V_{DF}$  condition (-7 V, 12 V), the buffer traps may be populated at two locations [5]: (1) drain-side of

the gate-edge because of the gate tunneling, and (2) G-D access region due to the applied voltage drop of  $V_{GD} = -19$  V. Similarly, the existence of disordered and clustered defects is anticipated at the gate-edge region. As a result,  $\tau_n$  increases with  $t_{fill}$  due to the defect-band-assisted trapping and detrapping phenomena, caused by the clustered buffer traps. The  $\Delta I_{DS}$  grows with  $t_{fill}$  and reaches saturation (resulting in fully ionized buffer traps) at 10 ms. Since the partial electron emission is probable during extended trap-filling times ( $t_{fill} > \tau_n$ ),  $\Delta I_{DS}$  decreases for  $t_{fill} \geq 100$  ms. The filling-pulse-induced variations in the emission time constant and DCT signal amplitude of the Fe-related traps F1 are shown in Fig. 4.

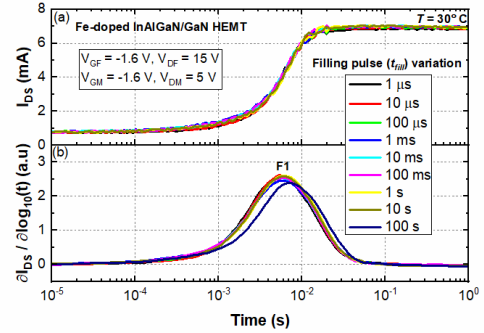


Fig. 1. (a) Single-pulsed drain-lag DCT spectroscopy and (b) derivative spectra of the Fe-doped InAlGaIn/GaN HEMT for different trap-filling pulse widths ( $t_{fill}$ ) ranging from 1  $\mu\text{s}$  to 100 s.

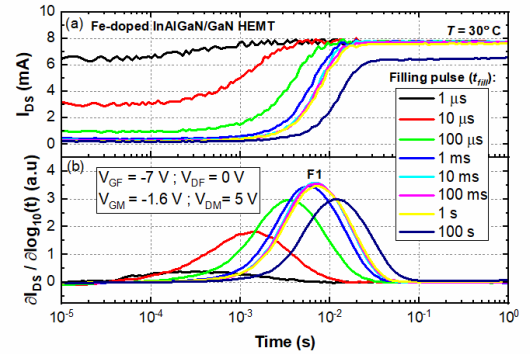


Fig. 2. (a) Double-pulsed DCT and (b) derivative spectra of the Fe-doped InAlGaIn/GaN HEMT attained upon OFF-state quiescent bias (-7 V, 0 V) at eight different pulse width durations ( $t_{fill}$ ).

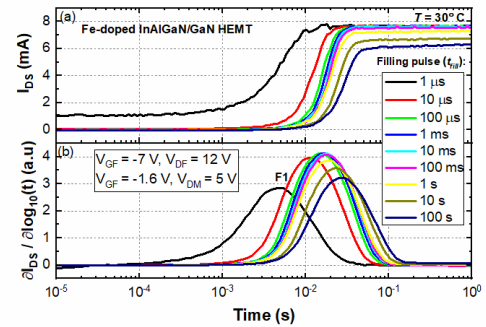


Fig. 3. (a) Double-pulsed DCT and (b) derivative spectra obtained upon deep-OFF-state quiescent biased stress (-7 V, 12 V) for various  $t_{fill}$ .

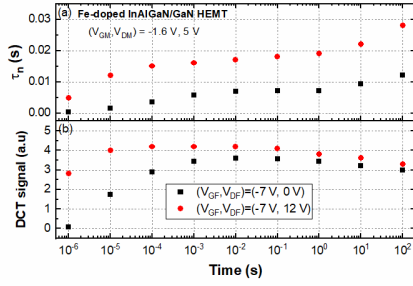


Fig. 4. Filling-pulse-width effects on  $\tau_n$  and the DCT signal amplitude of the Fe-related trap under OFF- and deep-OFF-state quiescent bias stress.

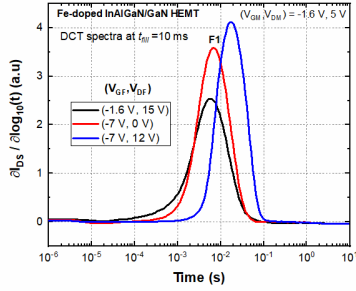


Fig. 5. Comparison of the DCT derivative spectra attained upon three different quiescent bias points at  $t_{fill} = 10$  ms for the Fe-related trap.

The DCT derivative spectra acquired upon three different quiescent bias points (semi-ON-, OFF- and deep-OFF-states) at  $t_{fill} = 10$  ms are compared in Fig. 5. The DCT signal amplitude is found to be maximum when the traps are populated under the deep-OFF bias (-7 V, 12 V), as this state can fill the buffer traps present in both the gate-edge and G-D access regions. Whereas, the  $\Delta I_{DS}$  is smaller for the single-pulsed drain-lag DCT case. Whenever the HEMT is exposed to the deep-OFF-state bias condition, high current collapse and dispersion effects are expected during the large-signal operation. The DCT results suggest that the trapping-induced dynamic drifts become more severe with the increased pulse width operation under OFF- and deep-OFF states. To improve the RF operation of the HEMT, the gate leakage current should be minimized, since it promotes the buffer trapping during the OFF-state conditions. Further optimization is required in the buffer growth process to mitigate the charge-trapping effects in the HEMTs.

### B. C-doped 0.1 $\mu\text{m}$ AlN/GaN HEMT

Figs. 6 and 7 show the DCT spectra for the C-doped AlN/GaN HEMT, attained upon the OFF-state (-6 V, 0 V) and deep-OFF state (-6 V, 10 V) quiescent bias stress. The  $\tau_n$  of the trap C1 increases with  $t_{fill}$ . But, we cannot extract the actual emission time constant of the trap C1 from the DCT peak maximum at 30 °C, as  $\tau_n$  is longer than the maximum acquisition time of 100 s. Thus, a slow detrapping behavior is detected for the trap C1 at  $E_C - 0.33$  eV in the C-doped AlN/GaN HEMT. Figs. 6 and 7 also reveal that  $\Delta I_{DS}$  grows with  $t_{fill}$ . These observations indicate that the current collapse

is more prominent in the C-doped HEMT, than the Fe-doped HEMT [5]. However, the filling-pulse-dependent DCT measurements need to be carried out at a higher temperature ( $T > 100$  °C) to understand the actual variation of  $\tau_n$  and  $I_{DS}$  and those experimental studies are underway.

## Conclusion

The DCT measurements show that  $\tau_n$  increases with  $t_{fill}$ , only if the HEMTs are exposed to the OFF- and deep-OFF state quiescent biases. For the Fe-related trap at  $E_C - 0.57$  eV,  $\Delta I_{DS}$  initially grows and reaches saturation at  $t_{fill} = 10$  ms. After that ( $t_{fill} \geq 100$  ms),  $\Delta I_{DS}$  decreases due to the partial electron emission, caused by the condition of  $t_{fill} > \tau_n$ . A slow detrapping transient ( $\tau_n > 100$  s at 30 °C) is detected for the trap at  $E_C - 0.33$  eV in the C-doped AlN/GaN HEMT.

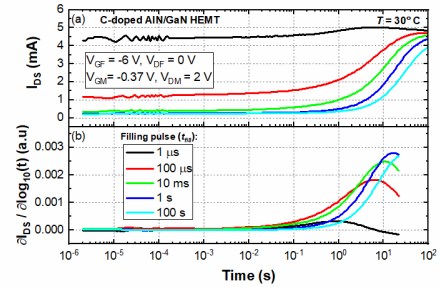


Fig. 6. Double-pulsed DCT and (b) derivative spectra of C-doped HEMT, obtained upon the OFF-state quiescent bias stress (-6 V, 0 V) for various  $t_{fill}$ .

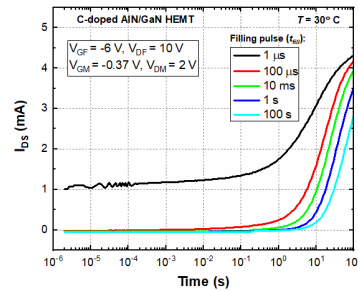


Fig. 7. Double-pulsed DCT and (b) derivative spectra of C-doped HEMT, obtained upon deep-OFF-state quiescent bias (-6 V, 10 V) for various  $t_{fill}$ .

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