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Experimental and Numerical Investigation of Poole-Frenkel Effect on Dynamic R_{ON} Transients in C-doped p-GaN HEMTs

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Abstract

In this paper, we investigate the influence of Poole-Frenkel Effect (PFE) on the dynamic R_{ON} transients in C-doped p-GaN HEMTs. To this aim, we perform a characterization of the dynamic R_{ON} transients acquired during OFF-state stress (i.e., $V_{GS,STR}$ = 0 V < V_T, $V_{DS,STR}$ = 25–125 V) and we interpret the results with the aid of numerical simulations. We find that dynamic R_{ON} transients at room temperature accelerate with $V_{DS,STR}^{1/2}$, which is signature of PFE, as further confirmed by the simultaneous decrease of the activation energy (E_A) extracted from the Arrhenius plot of the dynamic R_{ON} transients at $V_{DS,STR}$ = 50 V and T = 30–110 °C. Results obtained by means of calibrated numerical simulations reproduce the exponential dependence of transients time constants (τ) on $V_{DS,STR}^{1/2}$ and consequent E_A reduction only when including PFE enhancement of hole emission from dominant acceptor traps in the buffer related to C doping. This result is consistent with the model that considers hole emission from acceptor traps (rather than electron capture) as the mechanism underlying dynamic R_{ON} increase during OFF-state stress.

Keywords: p-GaN HEMTs, Dynamic ON-Resistance, Carbon Doping, Poole-Frenkel, "Hole-Redistribution" Model.

1. Introduction

P-GaN high electron mobility transistors (HEMTs) are an attractive technology option for power electronics thanks to their high voltage/speed operation and high current density capability [1]. By doping the buffer with Carbon impurities, the drain-source leakage current can be effectively reduced leading to increased breakdown voltage [2]. However, buffer traps related to C doping – in addition to other trapping mechanisms [3] – lead to collateral dispersion effects that cause stability issues such as threshold voltage (V_T) drift and dynamic R_{ON} increase [4], [5]. Being related to capture/emission dynamics of carriers from buffer traps, these dispersion effects can be influenced by electric-field enhancement mechanisms such as the Poole Frenkel Effect

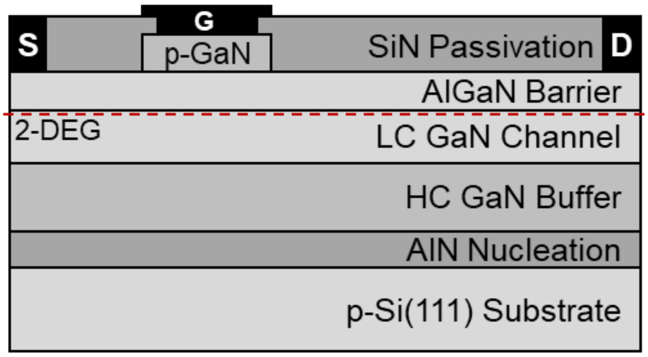

Fig. 1. Sketch of the p-Gate GaN HEMT device cross-section (not to scale).

(PFE) [6], [7]. However, a systematic analysis of the influence of PFE on R_{ON} evolution during OFF-state stress in p-GaN HEMTs is still lacking.

In this paper, we investigate the influence of PFE on dynamic R_{ON} transients during OFF-state stress (i.e., $V_{GS,STR} < V_T$, $V_{DS,STR}$ = 25-125 V) by means of both electrical characterization carried out on packaged p-GaN HEMTs and calibrated numerical device simulations [8]. Measurements reveal a dependence of the extracted time constants (τ) of dynamic R_{ON} transients on $V_{DS,STR}^{1/2}$, which can be attributed to PFE [6], [9], that also reflects on the reduction of the activation energy (E_A) extracted from the Arrhenius plot of the process. Results from the simulations obtained on a calibrated setup allow matching the experimentally observed τ vs $V_{DS,STR}^{1/2}$ behavior only when including PFE enhancement of hole emission from acceptor traps in the buffer related to C doping. This result further corroborates the model for the temperature-dependent dynamic R_{ON} increase during OFF-state stress (with $E_A \approx 0.9$ eV) as being due to hole emission rather than electron trapping [5], [10].

The remainder of the paper is organized as follows. In Section 2, the samples under test are described. Section 3 presents the experimental setup used for the OFF-state stress characterization as well as the models employed in the simulations. Experimental and simulation results are shown and discussed in Section 4. Finally, Conclusions are drawn in Section 5.

2. Samples Under Test

Samples are p-GaN gate AlGaN/GaN HEMTs in TO-220 packaging. The epitaxial structure (from bottom to surface) is as follows: the GaN buffer layer is 4.7 µm thick with high Carbon-doping concentration (~10^{18} cm^{-3}); the GaN channel consists of a 0.3-µm weakly C-doped layer (~10^{16} cm^{-3}); the $Al_{0.22}Ga_{0.78}N$ barrier is 15 nm thick. The *p*-type GaN layer forming the gate region is 100 nm thick and is Magnesium (Mg)-doped (~10^{19} cm^{-3}). The gate length is 1.5 µm, the gate-to-drain distance is 19 µm. The device cross-section is sketched in Fig. 1. The two-dimensional electron gas (2DEG) density is 8.6×10^{12} cm^{-2} and 2DEG mobility is 1.4×10^{3} $cm^2/(V\cdot s)$ [8]. More detailed description of the samples under test in this work is reported in [11].

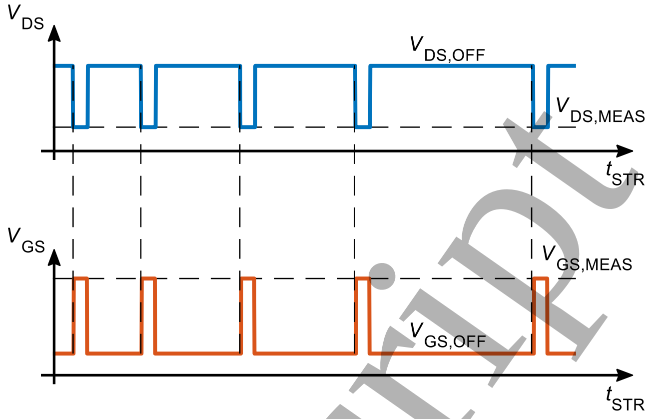

Fig. 2 Illustration of the V_{DS} and V_{GS} time sequences applied for the switch-mode characterization of dynamic R_{ON} transients during OFF-state stress.

3. Experimental and Simulation Setups

Dynamic R_{ON} transients were acquired by means of an in-house characterization setup, presented in [12]. OFF-state stress (i.e., $V_{GS,STR} = 0$ V $< V_T$, and high $V_{DS,STR}$) was carried out up to 1000 s of cumulative stress time (t_{STR}) by either varying $V_{DS,STR}$ in the range 25–125 V (at fixed temperature, T = 30 °C), or varying T in the range 30–110 °C (at fixed $V_{DS,STR}$ = 50 V). The reference ON-resistance value (R_{ON0}) was acquired on pristine samples (i.e., before the stress phase) at (V_{GS}, V_{DS}) = (6, 0.5) V. Dynamic R_{ON} was then monitored over the entire stress time range by periodically switching on the sample with fast 5-µs pulses at (V_{GS}, V_{DS}) = (6, 0.5) V, as illustrated in Fig. 2. R_{ON} was thus calculated as the V_{DS}/I_D ratio averaged over each 5-µs on-pulse.

Previous dynamic R_{ON} transients acquired on the same samples as those employed here (results shown in [11]) allowed extracting an activation energy (and time constants) consistent with values attributed to C-related traps by previous reports [6], [10], [13]. Accordingly, dynamic R_{ON} increase can be attributed to the increased negatively charged traps (associated with Carbon) in the gate-drain portion of the buffer region as a consequence of increasing hole emission [5].

Two-dimensional (2D) numerical device simulations were carried out with the SDevice™ simulator (Synopsys Inc.) [14]. The simulated device structure resembles that of the samples under test, see Fig. 1. Calibration of the simulation deck on the given device technology is reported elsewhere [11]. Drift-diffusion formalism was employed to simulate charge transport. Piezoelectric polarization at the heterointerfaces was accounted for by using the strain model included in the simulator. Mg-acceptors ionization energy was set to 0.16 eV from GaN valence band edge in the p-GaN gate region [11].

C doping in the GaN buffer was modeled by considering a dominant deep acceptor trap at 0.9 eV above E_V [15] partially compensated by a shallow donor trap at 0.11 eV below E_C [16], consistently with previous works [5], [17]. No additional traps were considered. Because channel thickness as well as gate-to-drain access region length influence dynamic R_{ON}

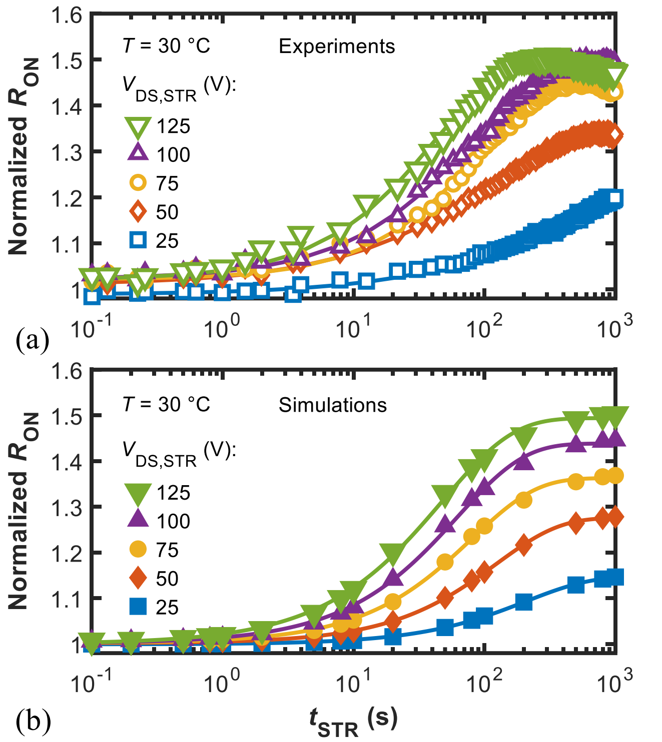

Fig. 3. (a) Experimental and (b) simulated R_{ON} vs t_{STR} transients taken at different $V_{DS,STR}$ (T = 30 °C), see legend. Both experiments and simulations exhibit an acceleration of the transients with increasing $V_{DS,STR}$. Solid lines are the stretched exponential functions used to fit the experimental (a) and simulated (b) data points.

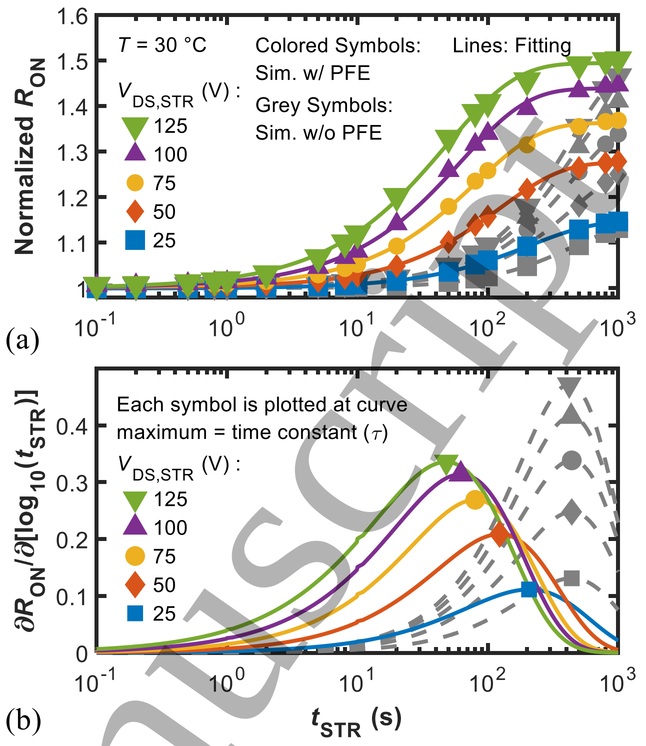

Fig. 4. Simulated (a) R_{ON} vs t_{STR} transients and (b) corresponding time derivative taken at different $V_{DS,STR}$ (T = 30 °C), see legend, with (colored symbols) and without (grey symbols) PFE. Simulations exhibit an acceleration of the transients (i.e., time constant τ reduction) with increasing $V_{DS,STR}$ only when PFE is included. Solid colored (dashed grey) lines are the stretched exponential functions used to fit the simulation data with (without) PFE.

dispersion, the same geometrical dimensions as those of the samples under test were employed in the simulations, see also [11].

PFE was taken into account with a model available in the simulator that computes the field-enhancement factor for the capture cross-section (σ) of acceptor traps $\beta = \exp[1/(k_BT)(q^3F/\pi\varepsilon)^{1/2}]$ (with q being the electron charge, k_B the Boltzmann constant, T the temperature, ε the dielectric constant of GaN, F the electric field) [14]. Thus, $\sigma \sim \sigma_0 \times \beta$, where σ_0 is the zero-field capture cross-section. This way, the barrier reduction induced by the applied electric field [9] and the consequent acceleration of hole emission from C-related acceptor traps (proportional to $\beta \sim V_{DS,STR}^{1/2}$) can self-consistently be taken into account in the simulations.

4. Results

Figure 3 shows the experimental (a) and (b) simulated dynamic R_{ON} transients for $V_{DS,STR}$ = 25–125 V and $V_{GS,STR}$ = 0 V at T = 30 °C. Note that in Fig. 3 (and following plots) dynamic R_{ON} values were normalized with respect to the pre-stress value $R_{ON,0}$. From Fig. 3(a) we observe and increase of the dynamic R_{ON} with increasing $V_{DS,STR}$ at fixed t_{STR} and, more importantly, a reduction of the transient time constants (τ). Both features are reproduced by the simulations as shown in Fig. 3(b). In this work, τ's are taken as the peaks of the time derivative of the dynamic R_{ON} curves, and the derivatives are computed on stretched exponential functions best fitting the data points [18], [19], as illustrated in Fig. 4(b).

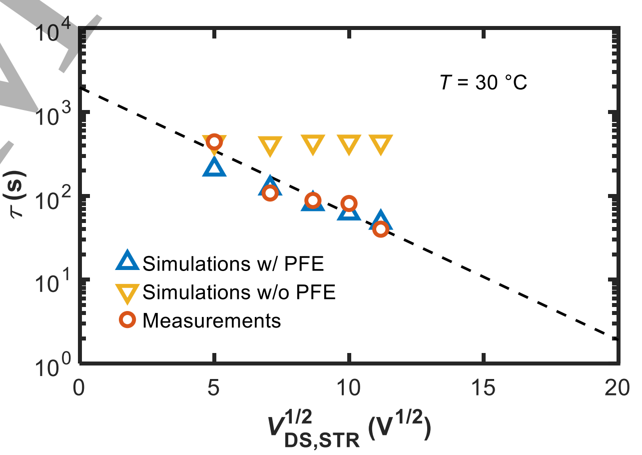

Fig. 5. Extracted time constants (τ) from experimental and simulated R_{ON} transients vs $V_{DS,STR}^{1/2}$ (y-axis is in log scale) at T = 30 °C. Black dashed line is a guide to the eye.

Fig. 4 compares the simulation results for the same $V_{DS,STR}$ range with and without PFE included in the set-up, clearly indicating the necessity of the field-enhancement model to reproduce the observed τ vs $V_{DS,STR}$ behavior. This point is further illustrated by Fig. 5, from which one can see that simulations reproduce the observed linear τ vs $V_{DS,STR}^{1/2}$ dependence (y-axis is in the log scale) only when including PFE.

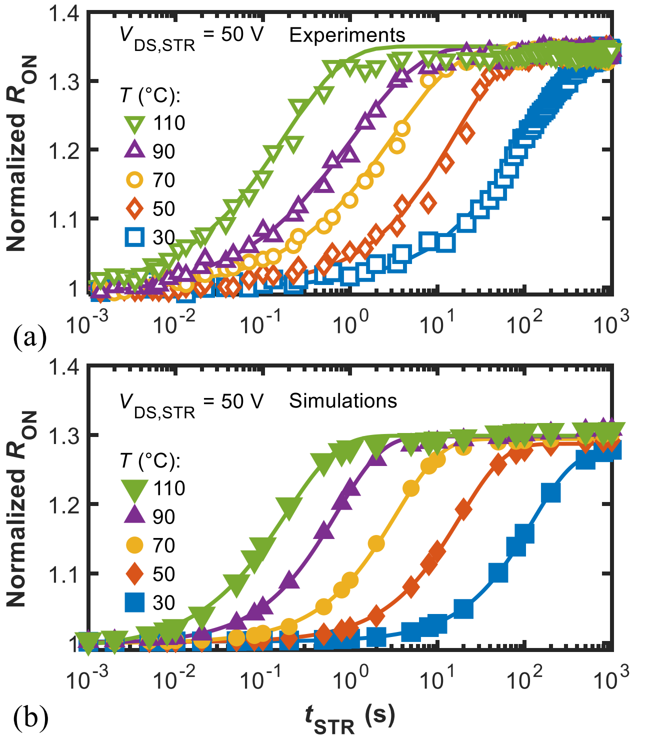

Fig. 6. (a) Experimental and (b) simulated R_{ON} vs t_{STR} transients taken at different T ($V_{DS,STR}$ = 50 V), see legend. Solid lines are the stretched exponential functions used to fit the experimental (a) and simulated (b) data points.

The reduction in the time constants influences the extraction of the trap parameters such as E_A from the Arrhenius plots. In fact, in general PFE causes a dependence of E_A on the applied field (i.e., on $V_{DS,STR}$) that needs to be taken into account to properly estimate the trap parameters [6]. Figure 6 shows the experimental (a) and (b) simulated dynamic R_{ON} transients for $V_{DS,STR}$ = 50 V and $V_{GS,STR}$ = 0 V at T = 30–110 °C. The E_A of the process extracted from the Arrhenius plots in Fig. 7 was estimated to be ≈ 0.7 eV for both experiments and simulations. When dominated by dispersion effects due to C-related buffer traps, dynamic R_{ON} transients acceleration with temperature was found to have an activation energy E_A ≈ 0.9 eV [5], [20], which correlates with the commonly accepted C-related acceptor trap energy level from GaN valence band [15]. However, as discussed previously the field-enhancement due to PFE of dynamic R_{ON} transients reduces E_A of the process with increasing $V_{DS,STR}$ due to reduction of τ (for each T), as shown in Fig. 7. As a consequence, experimental and simulated R_{ON} transients yield E_A ≈ 0.7 eV. Conversely, when PFE is not included the simulations yield E_A ≈ 0.83 eV. The E_A values extracted in this work are consistent with those extracted for C-related traps in a previous report also investigating the influence of PFE [6].

The results presented in this work clearly indicate that dynamic R_{ON} transients due to C-related traps are influenced by field-enhancement mechanisms such as PFE. Incidentally, we observe that the energy barrier reduction via PFE is theoretically expected for trap states acting as Coulomb

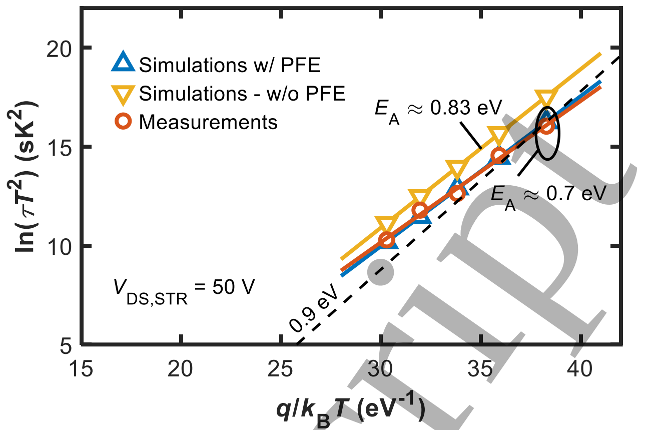

Fig. 7. Arrhenius plot extracted from experimental and simulated R_{ON} transients at $V_{DS,STR}$ = 50 V. Black dashed line is a guide to the eye with slope 0.9 eV (i.e., commonly accepted C-related acceptor trap level [15]).

centers, which is the case for acceptor traps emitting holes to the valence band [9]. This behavior agrees with the model considering hole emission (rather than electron capture) to be the root cause of temperature-dependent dynamic R_{ON} increase during OFF-state stress [5], [10].

5. Conclusions

We investigated the influence of PFE on the dynamic R_{ON} transients during OFF-state stress in p-GaN HEMTs. Electrical characterization of transients taken at different drain stress bias ($V_{DS,STR}$) revealed a square-root dependence of the extracted time constants of the dynamic R_{ON} transients on $V_{DS,STR}$, which is signature of PFE. Numerical simulations performed on a calibrated deck allowed reproducing the experimental results only when including PFE enhancement of hole emission from acceptor traps in the buffer related to C doping. The consequent reduction of the activation energy of the process observed in the experiments is also reproduced by the simulations. This result further corroborates the model considering hole emission (rather than electron capture) to be the mechanism underlying the dynamic R_{ON} increase during OFF-state stress.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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