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Effect of Trap-Filling Bias on the Extraction of the Time Constant of Drain Current Transients in AlGaN/GaN HEMTs

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Summary. We investigate the influence of trap filling conditions on the extraction of the emission time constant (τ) of deep levels associated with Fe doping in AlGaN/GaN HEMTs. To this end, we monitor the drain current transients (DCTs) after a short (1 μs) trap filling pulse and investigate the effect of varying the drain voltage ($V_{DS,fill}$) applied. We find that the extracted τ decreases for $V_{DS,fill}$ below 30 V; instead, for $V_{DS,fill}$ > 30 V τ saturates to a value corresponding to the inverse of the emission rate ($1/e_n$). The decrease of τ with decreasing $V_{DS,fill}$ was explained, for the first time, with the aid of numerical simulations, attributing it to the concurrent effect of both emission and capture processes during DCT. This helps to correctly characterize the trap dynamics, avoiding errors in the estimation of e_n from DCTs.

Motivation. The measurement of Drain Current Transients (DCTs) induced by trapping phenomena, is routinely used for the characterization of deep-levels in AlGaN/GaN high electron mobility transistors (HEMTs), since it provides a fast tool for measuring the charge emission rate (e) from traps [1]. However, the emission time constants ($\tau_e=1/e$) extracted with this method could be affected by the trap filling conditions employed for the measurements [2], thus affecting the study of the trap dynamics. Aim of this paper is to investigate and explain the influence of the trap filling bias on the extraction of τ_e from DCTs.

Results. Devices under test (DUTs) were AlGaN/GaN single heterojunction HEMTs presenting an iron (Fe) doped GaN buffer. DCTs induced by trapping phenomena have been measured with the double-pulse method sketched in Fig. 1 (see [3] for further details). A single exponential transient was observed and thermal dependent measurements were carried out to estimate the trap activation energy (E_A) [3]. The linear fit of the Arrhenius plot of Fig. 2 yielded E_A = 0.52 eV, which is consistent with values reported for Fe-related buffer traps [4]. To assess the effect of $V_{DS,fill}$ on the DCTs, we kept $V_{GS,fill}$ constant at −3.8 V while varying $V_{DS,fill}$. Results obtained for $V_{DS,q}$=10 V and $I_{D,q}$=50 mA/mm are shown in Fig. 3(a). From Fig. 3(a) we observe that the DCT amplitude reduces while reducing $V_{DS,fill.}$ Moreover, a reduction in $V_{DS,fill}$ yields an apparent speed-up in the DCTs, causing the peak in the $dI_D/d\log_{10}t$ signal to move towards shorter times, see Fig. 3(b). To gain insights in this behavior, 2D numerical simulations were performed (see Fig 4) and, similarly to the experiments, the extracted τ move towards shorter times when reducing $V_{DS,fill,}$ while approaching the theoretical $1/e_n$ value for $V_{DS,fill}$ > 30 V (see Fig. 5). This variation of τ can be explained by the Shockley-Read-Hall theory, according to which the differential equation governing the time-dependent trap occupancy (n_T) of electrons is $dn_T/dt=c_n n(N_T\text{-}n_T)\text{-}e_n n_T$ (1) [5]. If the electron capture is negligible w.r.t. electron emission, equation (1) reduces to $dn_T/dt=\text{-}e_n n_T$ (2), whose solution is a pure exponential function, i.e., $n_T(t)=n_T(0)\exp(-t\times e_n)$. On the other hand, when the term $c_n n(N_T-n_T)$ is not negligible, the time evolution of the trapped/emitted charge deviates from (1) as described by (2). As a consequence, the τ extracted from the resulting DCT is different from $1/e_n$. This discrepancy is the cause for the observed τ-dependence on $V_{DS,fill}$. We verified this interpretation by comparing the time evolution of the simulated n_T with the one calculated with equations (1) and (2). Figs. 6(a) and 6(b) show the results obtained at $V_{DS,fill}$ = 20 V and $V_{DS,fill}$ = 60 V, respectively. At $V_{DS,fill}$ = 20 V, the term $c_n n(N_T-n_T)$ is non-negligible, yielding a speed-up of the observed DCT, with a consequent reduction in the extracted τ. On the other hand, for $V_{DS,fill}$ = 60 V, the emission is weakly affected by the capture induced at ($V_{DS,q}$;$V_{GS,q}$) and the τ extracted from the DCT can be correctly used for estimating e_n.

References. [1] J. Joh, et al., IEEE TED, vol. 58, no. 1, 2011. [2] A. M. Angelotti, et al., IEEE TED, vol. 67, no. 8, 2020. [3] M. Cioni, et al., IEEE TED, 2021. [4] O. Axelsson, et al., IEEE TED, vol. 63, no. 1, 2016. [5] D. K. Schroder, Wiley (2005).

Figures

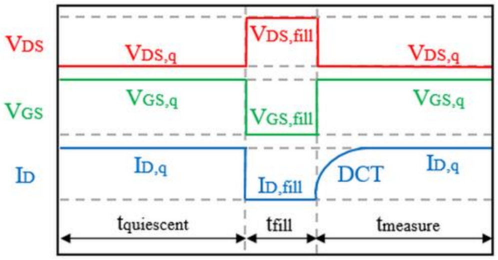

Fig. 1: Typical DCTs measurement sequence. The DUT is first biased at ($V_{DS,q}$;$V_{GS,q}$). Then, a 1 μs filling pulse ($V_{DS,fill}$; $V_{GS,fill}$) is applied in order to fill buffer traps. The DUT is then biased back at ($V_{DS,q}$; $V_{GS,q}$), and the I_D recovery is monitored over several time decades ($t_{measure}$).

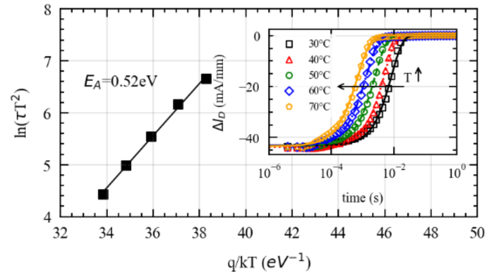

Fig. 2: Arrhenius plot corresponding to the trap state responsible for DCTs (linear fitting yields E_A=0.52 eV). The inset shows measured DCTs for temperature (T) between 30°C and 70°C.

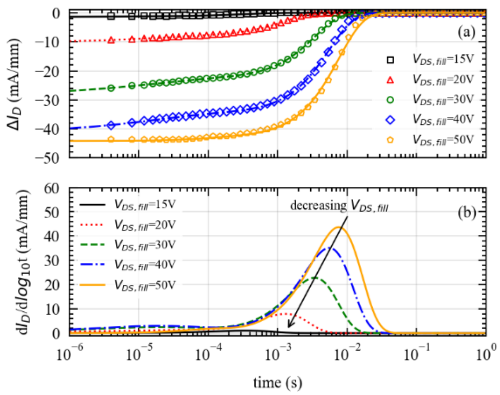

Fig. 3: (a) Measured DCTs taken at different $V_{DS,fill}$ and $V_{GS,fill}$ = −3.8 V. The current variation (ΔI_D) is with respect to $I_{D,q}$=50 mA/mm. (b) $dI_D/d\log_{10}t$ used for extracting τ.

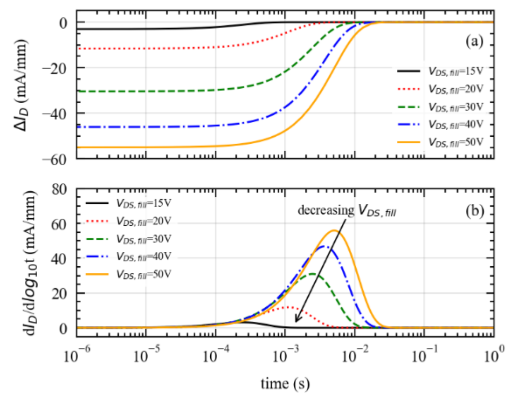

Fig. 4: (a) Simulated DCTs taken at different $V_{DS,fill}$ and $V_{GS,fill}$=−3.8 V (i.e., ~1 V below the device V_{TH}). (b) $dI_D/d\log_{10}t$ used for extracting the emission time constant (τ).

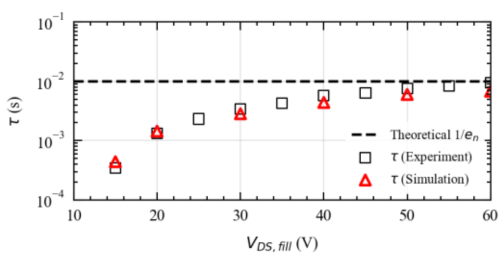

Fig. 5: Emission time constants (τ) extracted from measured and simulated DCTs at several $V_{DS,fill}$ levels and $V_{GS,fill}$=−3.8 V. A variation on $V_{Ds,fill}$ < 30 V yields a significant variation on τ, while data collected at high $V_{DS,fill}$ approach the inverse of the trap emission rate ($1/e_n$).

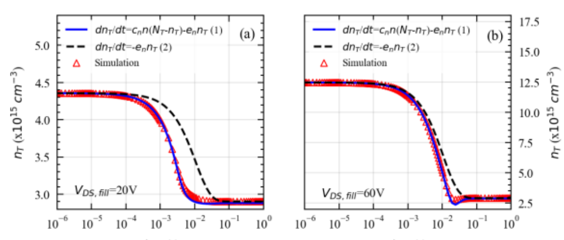

Fig. 6: Comparison between n_T obtained from simulation and n_T computed with (1) and (2). (a) At $V_{DS,fill}$ = 20 V, the capture contribution is non-negligible, yielding a difference in the extracted τ. (b) At $V_{DS,fill}$ = 60 V, the emission is dominant, yielding overlapped transients.