# On the Effect of Interface Traps on the Carrier Distribution Function During Hot-Carrier Degradation

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***Abstract*—We study the effect of interface states, generated during hot-carrier stress, on the carrier energy distribution functions (DFs) and check whether this effect perturbs the results of our hot-carrier degradation model. These studies are performed using SiON nMOSFETs with a gate length of 65 nm as exemplary devices. We carry out simulations with different values of the spatially uniform interface state density ($N_{\mathrm{it}}$) as well as with a coordinate dependent $N_{\mathrm{it}}$ evaluated for real stress conditions. In both cases, the effect of $N_{\mathrm{it}}$ on carrier distribution functions appears to be strong. As for the degradation characteristics, we show that $N_{\mathrm{it}}$ profiles computed with perturbed distribution functions can be substantially different from those obtained with non-perturbed DFs, especially at long stress times. The same trend is visible also for changes in the linear drain current. Additional simulations performed for operating conditions with and without the effect of $N_{\mathrm{it}}$ show that if this effect is not taken into account, this leads to severe underestimation of the device life-time.**

## I. INTRODUCTION

Hot-carrier degradation (HCD) is driven by single- and multiple-carrier processes of Si-H bond dissociation [1–3]. These processes are induced by hot and cold carriers, respectively, and the only way to distinguish between these types of carriers is related to the solution of the Boltzmann transport equation and obtaining the carrier energy distribution function (DF). The carrier DF is needed to calculate the rates of these two bond-breakage mechanisms (and all their superpositions [4–8], see Fig. 1) and hence the cumulative bond dissociation rate. The idea that proper physical modeling of HCD requires the carrier DF has been acknowledged by different groups [4, 6, 9–12] and also implemented in our HCD model [8, 13–15]. In all these models the DF is computed just once for the pristine device and the effect of generated interface traps (with a density $N_{\mathrm{it}}$) on the DF shape is ignored. This is because solving the Boltzmann transport equation is a computationally challenging task. However, we expect that typical $N_{\mathrm{it}}$ values accumulated during long-term degradation can significantly perturb the carrier energy distribution and therefore affect the bond-breakage rate.

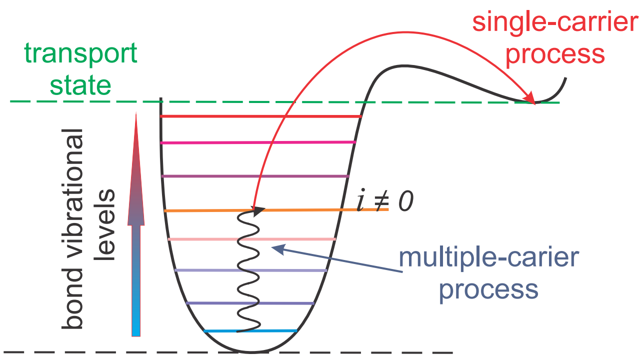

Fig. 1. A schematic representation of the single- and multiple-carrier mechanisms of Si-H bond rupture. The former process is induced by a solitary hot carrier, while the latter one is triggered by several cold carriers which subsequently bombard the bond.

Here, we investigate the impact of $N_{\mathrm{it}}$ on the carrier DF and the importance of this effect. We also study whether the effect of generated interface traps on the distribution functions translates into a discrepancy in the degradation of device characteristics (such as the linear drain current change) evaluated with perturbed and non-perturbed DFs. We use our HCD model which was validated against experimental data acquired over a wide class of devices and stress conditions [8, 15, 16] without the effect of $N_{\mathrm{it}}$ and analyze how the results will change if $N_{\mathrm{it}}$ is taken into account. Considering this effect will substantially increase the model complexity as well as computational demands and thus we perform a check of the effect importance.

## II. THE FRAMEWORK

Our physics-based model for hot-carrier degradation [8, 15] captures and links three main aspects related to HCD, i.e. a thorough carrier transport description, modeling the rates of Si-H bond-breakage mechanisms on the microscopic level, and simulations of the degraded devices.

The transport sub-task of the HCD problem is solved using the deterministic Boltzmann transport equation solver ViennaSHE [17, 18] which employs the spherical harmonics expansion method. ViennaSHE is used to compute the carrier energy distribution functions for a specified device architecture and applied stress conditions. While computing DFs we consider the effect of electron-electron scattering because this process populates the high energetical fraction of the carrier ensemble and therefore enhances hot-carrier degradation [19–22].

The calculated DFs are employed to model single- and multiple-carrier processes and evaluate the bond dissociation rate. Our model considers all superpositions of these two mechanisms, i.e. the bond can first be pre-heated by several

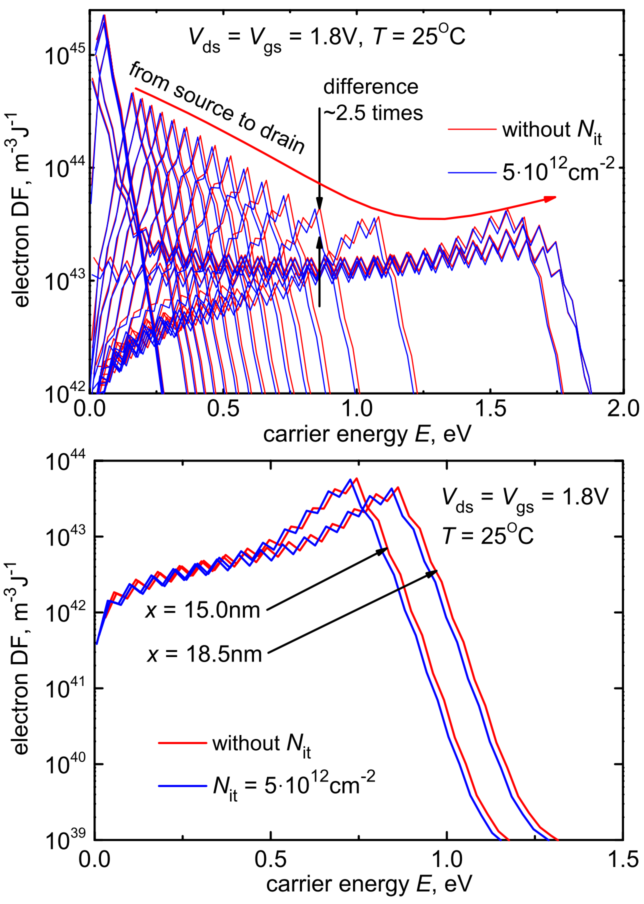

Fig. 2. The DFs calculated for $V_{\mathrm{ds}}$ = $V_{\mathrm{gs}}$ = 1.8 V with and without the effect of a fixed $N_{\mathrm{it}}$ value of $5{\times}10^{12}\mathrm{cm}^{-2}$ and for different positions in the device (the arrow represents the source-to-drain direction; here source is at $x$ = -32.5 nm, the drain is at +32.5 nm). The difference in DFs is mostly pronounced at $x$ = 15.0 and 18.8 nm.

cold carriers which induce the multiple vibrational excitation of the bond and then ruptured by a solitary high energetical particle (see Fig. 1). The generated $N_{\mathrm{it}}$ profiles are then used as input to simulate the characteristics of the degraded device for each stress time step. In order to study the effect of $N_{\mathrm{it}}$ on carrier transport we extended ViennaSHE in a manner to incorporate interface traps. Their effect is twofold: charged states perturb the local band bending (this effect is considered in the Poisson equation) and act as additional scattering centers (this rate enters the Boltzmann equation).

As an exemplary device we use an n-channel MOSFETs with a gate length of 65 nm (the channel length is $\sim$ 45 nm) and a 2.5 nm SiON layer. These transistors have been subjected to hot-carrier stress at $V_{\mathrm{ds}}$ = $V_{\mathrm{gs}}$ = 1.8 and 2.0 V ($V_{\mathrm{ds}}$ and $V_{\mathrm{gs}}$ are drain and gate voltages, respectively) for $\sim$ 8.8 ks at room temperature. HCD was assessed by monitoring the linear drain current change with time $\Delta I_{\mathrm{d,lin}}(t)$ ($I_{\mathrm{d,lin}}$ was measured at $V_{\mathrm{ds}}$ = 0.05 V and $V_{\mathrm{gs}}$ = 1.5 V).

## III. RESULTS AND DISCUSSION

To check the magnitude of the effect $N_{\mathrm{it}}$ has on the DFs' and the degradation traces $\Delta I_{\mathrm{d,lin}}(t)$, we have calculated a series of electron distribution functions for an artificial case of a spatially uniform $N_{\mathrm{it}}$ value. Fig. 2 summarizes DFs obtained for $V_{\mathrm{ds}}$ = $V_{\mathrm{gs}}$ = 1.8 V with and without the effect of $N_{\mathrm{it}}$ = $5{\times}10^{12}\mathrm{cm}^{-2}$. One can see that the most prominent difference between these DFs is visible in the drain-ended area of the channel, i.e. at the lateral coordinate $x$ of 15.0 and 18.8 nm (the source corresponds to $x$ = -32.5 nm, while the drain is at $x$ = +32.5 nm). Fig. 2 demonstrates that an $N_{\mathrm{it}}$ of $5{\times}10^{12}\mathrm{cm}^{-2}$ reduces the population of the DF high-energy tail by a factor of ~2.5. This behavior is not related to the localized nature of HCD but stems from the superposition of two factors: ($i$) the device performance is most severely affected by traps generated in the channel [23, 24] and ($ii$) carriers typically have highest average energies at the drain end of the channel [3, 13]. Fig. 3 shows $\Delta I_{\mathrm{d,lin}}(t)$ traces simulated considering and neglecting the impact of interface traps for three values of $N_{\mathrm{it}}$ uniform in space with $N_{\mathrm{it}}$ = $2{\times}10^{12}$, $5{\times}10^{12}$, and $10^{13}\,\mathrm{cm}^{-2}$. As a reference, we also

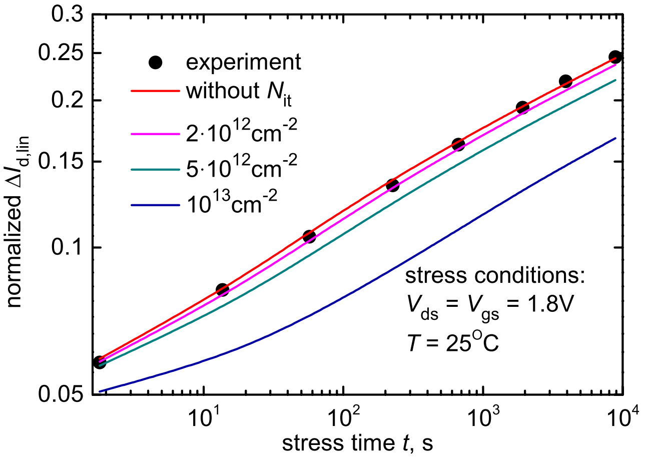

Fig. 3. The $\Delta I_{\mathrm{d,lin}}(t)$ traces obtained with and without the effect of $N_{\mathrm{it}}$ on the carrier DFs. The experimental $\Delta I_{\mathrm{d,lin}}(t)$ curve (used as a reference) was represented by the model with good accuracy. However, if the effect of $N_{\mathrm{it}}$ is considered the model fails to capture the $\Delta I_{\mathrm{d,lin}}(t)$ change.

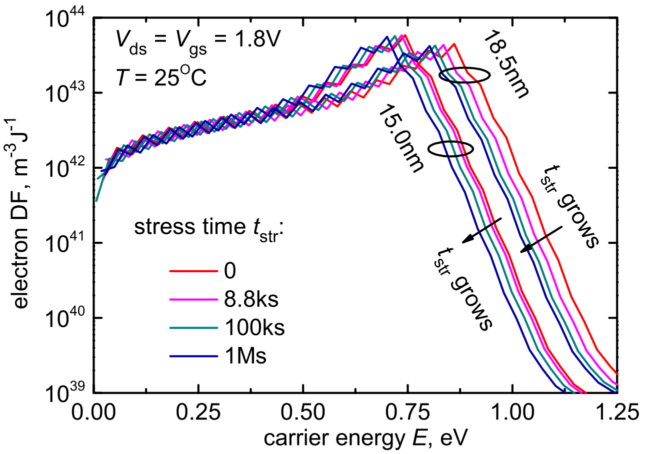

Fig. 4. The electron distribution functions calculated for $V_{\mathrm{ds}}$ = $V_{\mathrm{gs}}$ = 1.8 V with and without the effect of $N_{\mathrm{it}}$. In the latter case stress times of 8.8 ks, 100 ks, and 1 Ms are chosen.

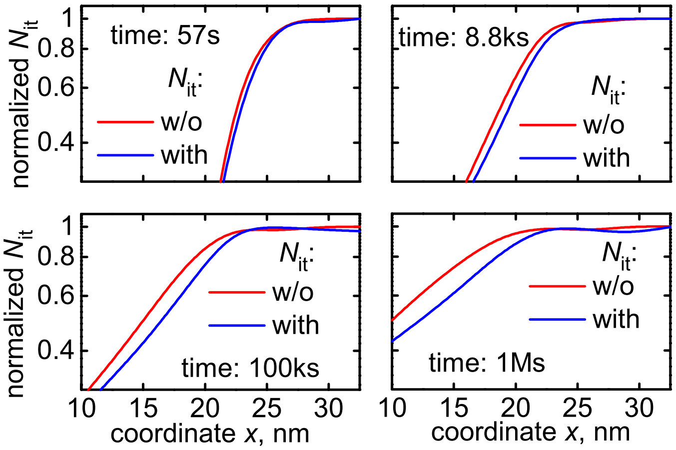

Fig. 5. The interface state density profiles (normalized to the concentration of virgin Si-H bonds) calculated considering and neglecting the effect of $N_{\rm it}$ on the carrier DFs for $V_{\rm ds}$ = $V_{\rm gs}$ = 1.8 V. To provide better visibility we show only the drain half of the device.

provide experimental data which were well represented by the model without the $N_{\rm it}$ effect [15]. However, at $N_{\rm it}$ = $2{\times}10^{12}{\rm cm}^{-2}$ some deviations start to be visible and for $N_{\rm it}$ = $5{\times}10^{12}{\rm cm}^{-2}$ these deviations become very strong. These findings suggest that a self-consistent treatment of interface trap generation kinetics and carrier transport is needed.

To study this effect in greater detail, we have simulated electron DFs for $V_{\rm ds}$ = $V_{\rm gs}$ = 1.8 V. Fig. 4 shows a comparison between DFs obtained without the effect of $N_{\rm it}$ and those computed considering this effect for three stress time steps of 8.8 ks, 100 ks, and 1 Ms. One can see that already at 8.8 ks the electron DFs visibly change their shape. We also plot normalized (to the maximum $N_{\rm it}$ value which corresponds to the density of pristine Si-H bonds) interface state density profiles obtained with and without the effect of $N_{\rm it}$ on the carrier distribution function, see Fig. 5. It can be concluded that the $N_{\rm it}$ profiles change substantially, especially at longer times. This trend appears to be reasonable because at long-term stress the damage is stronger and hence changes the carrier DFs more. Fig. 6 depicts degradation traces for $V_{\rm ds}$ = $V_{\rm gs}$ = 1.8 and 2.0 V plotted against experimental data. It is clearly shown that if the effect of $N_{\rm it}$ on the DFs is introduced, $\Delta I_{\rm d,lin}(t)$ does no longer match the experimental data and the discrepancy increases with stress time.

Although the discrepancy in the $N_{\rm it}$ profiles and $\Delta I_{\rm d,lin}$ traces is pronounced, it is important to understand whether it disrupts predictive capabilities of the model. We have therefore simulated the $\Delta I_{\rm d,lin}(t)$ dependencies for conditions close to the operating ones, i.e. for $V_{\rm ds}$ = $V_{\rm gs}$ = 1.0 V for stress time up $4{\times}10^8$ s (~12 years), Fig. 7. The trace simulated considering the effect of $N_{\rm it}$ starts to bend towards lower values at ~100 ks. At a first glance, even after $4{\times}10^8$ s the discrepancy looks weak. However, if one uses these traces to estimate the device life-time as the time when the relative current degradation reaches a threshold of 5%, the difference in the results will be dramatic, i.e. ~3 months against vs. ~11.5 months. This suggests that the effect of $N_{\rm it}$ on HCD modeling can be strong and one needs to consider carrier transport and generation of interface states self-consistently. We expect that the extended model which captures the interplay between the interface state generation mechanisms and carrier transport is more physically complete and will provide a more accurate description of HCD.

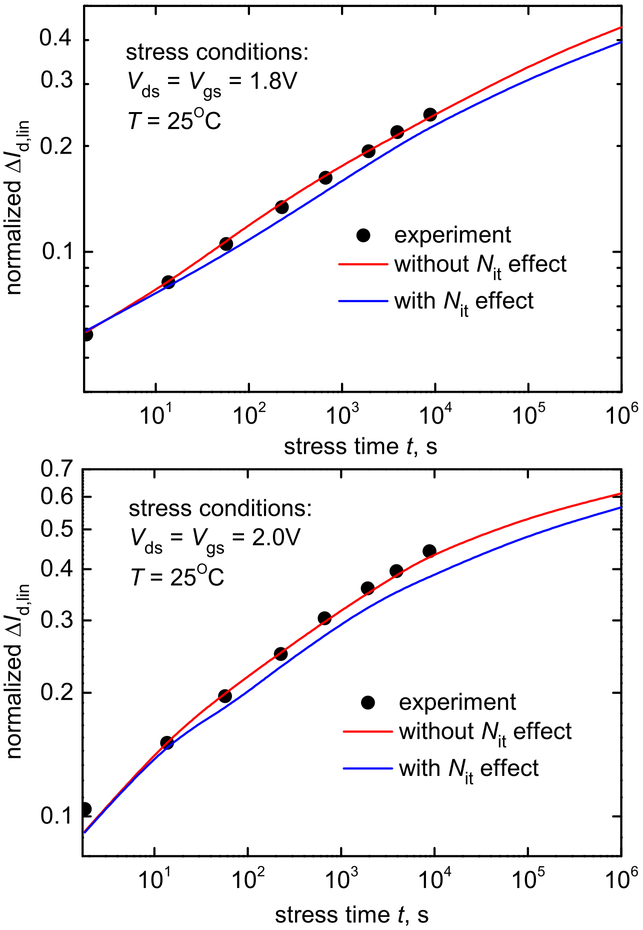

Fig. 6. The $\Delta I_{\rm d,lin}$ changes as a function of stress time plotted for two stress conditions: $V_{\rm ds}$ = $V_{\rm gs}$ = 1.8 (upper panel) and 2.0 V (lower panel). If the effect of interface traps on the carrier DF is considered, this can substantially change $\Delta I_{\rm d,lin}$ values.

## IV. CONCLUSION

We have studied the effect of interface traps on the carrier distribution function and the linear drain current change $\Delta I_{\rm d,lin}(t)$ under hot-carrier stress conditions as well as at operating voltages. At stress conditions, the effect is pronounced and can substantially change the shape of the DFs. Note that DFs are mostly affected at the drain end of the gate which is consistent with previous findings. As for interface state density profiles $N_{\rm it}(x)$ and $\Delta I_{\rm d,lin}(t)$ traces, the discrepancy in distribution functions translates into a significant difference in $N_{\rm it}$ and $\Delta I_{\rm d,lin}$ values and this effect appears to be stronger at longer stress times. As for operating conditions, at a first glance, the difference between the $\Delta I_{\rm d,lin}$ changes

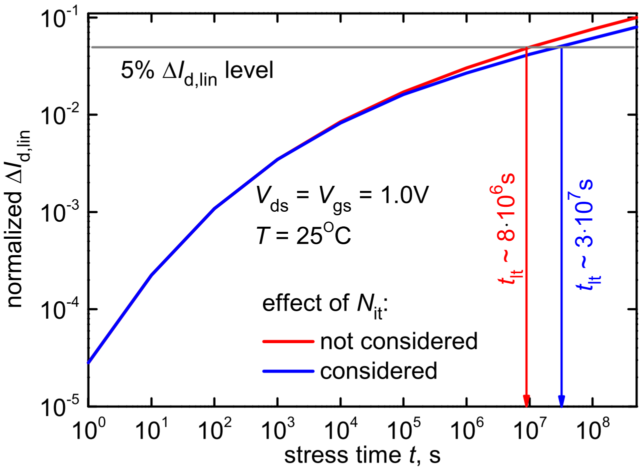

Fig. 7. The $\Delta I_{\rm d,lin}$ changes simulated for $V_{\rm ds}$ = $V_{\rm gs}$ = 1.0 V with and without the $N_{\rm it}$ effect up to ∼12 years. Due to the discrepancy in $\Delta I_{\rm d,lin}(t)$ curves, the values of the device life-time extracted using them differ by more than 3 times.

appears insignificant. However, the values of the device life-time extracted using these $\Delta I_{\rm d,lin}(t)$ dependencies differ by a factor of 3. All this suggests that proper modeling of hot-carrier degradation requires self-consistent consideration of carrier transport and interface state generation. We believe that the model extended in a manner to incorporate the interplay between interface trap generation and carrier transport will provide a more complete physical description of HCD.

## ACKNOWLEDGMENT

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