Impact of the Carrier Distribution Function on Hot-Carrier Degradation Modeling

Stanislav Tyaginov, Ivan Starkov, Christoph Jungemann, Hubert Enichlmair, Jong-Mun Park, and Tibor Grasser.

***Abstract*—We employ a physics-based model for hot-carrier degradation (HCD), which includes three main sub-tasks: the carrier transport module, a module describing interface state generation and a module for the simulation of the degraded devices. We examine different realizations of the model: with the transport module represented by Monte-Carlo, energy transport and drift-diffusion schemes. The main version, based on the Monte-Carlo approach, is able to represent HCD observed in different MOSFETs using the same set of the model parameters. These parameters have reliable and physically reasonable values. Therefore, we check whether two other versions are capable of the same representation (with the same parameters) or not. It appears that the simplified treatments fail to describe the degradation in devices of the same architecture but with different channel lengths employing a unique set of parameters. This circumstance suggests that a comprehensive HCD model has to be based on a rigorous solution of the Boltzmann transport equation (e.g. by means of a Monte-Carlo method).**

***Index Terms*—hot-carrier degradation, Monte-Carlo, energy transport model, drift-diffusion model, interface states, TCAD.**

I. INTRODUCTION

A comprehensive model for hot-carrier degradation (HCD) should carefully understand and capture the physical picture behind this detrimental effect. This means that essential peculiarities of this phenomenon have to be represented by the model. Among them are the interplay between single- and multiple-particle mechanisms (SP- and MP-processes) of Si-H bond dissociations [1]–[4], the strong localization of the damage [5], [6] and the degradation saturation achieved at long stress times [4], [7]. Finally, the damage induced not only by the minority carriers (forming the channel) but also by the majority carriers is to be considered [8], [9]. Physical mechanisms triggering HCD and incorporated into the model are characterized by corresponding parameters. It is rather important that these parameters have physically reasonable values. Moreover, a reliable and physics-based model should be able to represent HCD observed in geometrically scaled devices using the same set of the model parameters.

The driving force of HCD is the energy deposited by charge carriers. Their ensemble may be conditionally separated into "hotter" and "colder" fractions. A "hotter" carrier can trigger a bond dissociation process in a single collision, i.e. launch a single-particle process. At the same time a multiple-carrier induced bond dissociation includes the interaction of a bond with several "colder" particles. Since the carrier packet is characterized by energies covering a wide range, the interplay between SP- and MP-processes has to be respected. The demand that the model captures the interplay between SP- and MP-processes presumes a criterion for separating between "hotter" and "colder" particles. This criterion may be based on the electric field or the carrier average energy, etc. However, the most rigorous way is based on the calculation of the carrier energy distribution function (DF). This information may only be achieved by solving the Boltzmann transport equation. Hence, a comprehensive HCD model has to essentially include a module responsible for the carrier transport treatment.

We already presented a physics-based model for hot-carrier degradation which is based on the solution of the Boltzmann transport equation [10]–[12] by means of a full-band Monte-Carlo (MC) device simulator MONJU [13]. However, Monte-Carlo simulations are time consuming and their substitution by faster simplified schemes – like energy-transport (ET) and drift-diffusion (DD) models [14] – for Boltzmann transport equation (BTE) solving appears very attractive. There is a considerable amount of papers (see e.g. [15], [16] and the references therein) devoted to the comparison between different transport schemes and showing that ET and DD models fail to properly describe hot carriers in the case of a channel length less than 0.10 μm. A detailed analysis of results obtained with MC, ET and DD approaches to the BTE solution was performed in [15] confirming that ET and DD schemes may be applicable for channel lengths more than 0.1 μm. Our HCD model has been verified using MOSFETs with a channel length more than 0.5 μm. In these long-channel devices the SP-mechanism plays the dominant role. Just the SP-mechanism is triggered by the "hottest" carriers, i.e. is defined by the high-energy tail of the DF. As a consequence, HCD modeled for this case will be most sensitive to the chosen transport scheme.

Therefore, is appears mandatory to investigate whether simplified treatments of carrier transport may be successfully employed in the model to substitute the time-consuming Monte-Carlo method. Thus, this work aims to compare different (i.e. based on Monte-Carlo, energy transport and drift-diffusion methods) realizations of our HCD model.

II. EXPERIMENTAL SUPPORT

To verify these model versions we employed three 5V n-MOSFETs of the same architecture (fabricated on a standard

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0.35 μm process), but different only in channel lengths ($L_{\rm ch}$ = $0.5, 1.2$ and 2.0 μm). Devices were stressed at a gate voltage $V_{\rm gs}$ = 2.0 and a drain voltage of $V_{\rm ds}$ = 6.25 V at 25$^{\rm o}$ C).

III. The model

Our HCD model incorporates three main modules: the carrier transport module, the module describing microscopic mechanisms for defect creation, and the module responsible for simulations of degraded device characteristics (Fig. 1). The first module calculates the distribution function for both types of carriers for a particular device architecture and given stress conditions. This DF is then used to calculate the electron and hole acceleration integrals as a function of the coordinate x along the interface: $I = \int f(E)g(E)\sigma(E)v(E)dE$, where $f(E)$ is the carrier DF, $g(E)$ the density-of-states, $\sigma(E)$ the reaction cross section, $v(E)$ the carrier velocity and integration is performed over energy starting from the threshold for the Si-H bond dissociation reaction. The acceleration integrals control both SP- and MP-processes and thus allow us to calculate the interface state density profile $N_{\rm it}(x)$ at each time step. Note that even in the case of high-voltage devices the MP-mechanism contributes considerably to the damage [10]. The information about the interface state concentration is then loaded into the device simulator MINIMOS-NT [17] which calculates the degraded device characteristics at each time step. These calculations are performed considering that charged interface states perturb the electrostatics of a MOSFET and the carrier mobility.

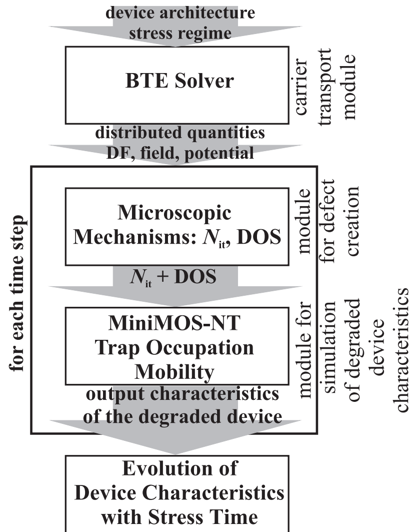

Fig. 1. The simulation flowchart. The modeling concept includes the transport module, the module for trap generation, and the module responsible for simulations of characteristics of a degraded device.

Our approach has been carefully verified in order to represent the degradation observed in MOSFETs with 3 different channel lengths [12]. The model incorporates the secondary generated holes. It is worth mentioning that the relative contribution into the total $N_{\rm it}$ produced by holes is relatively small. Nevertheless, this portion of $N_{\rm it}$ impacts the linear drain current comparable to that induced by channel electrons. The reason is that the interface states generated by electrons are

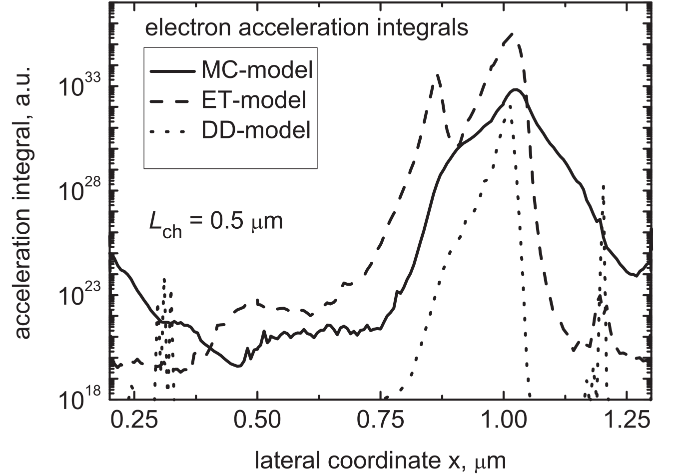

Fig. 2. The electron acceleration integral calculated with MC-, ET-, and DD-based versions of our HCD model for the case of $L_{\rm ch} = 0.5\mu$m.

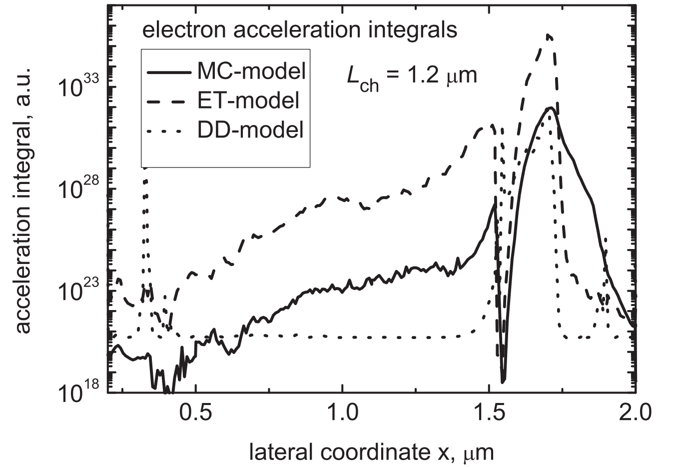

Fig. 3. The electron acceleration integral calculated with with MC-, ET-, and DD-based versions of our HCD model for the case of $L_{\rm ch} = 1.2\mu$m.

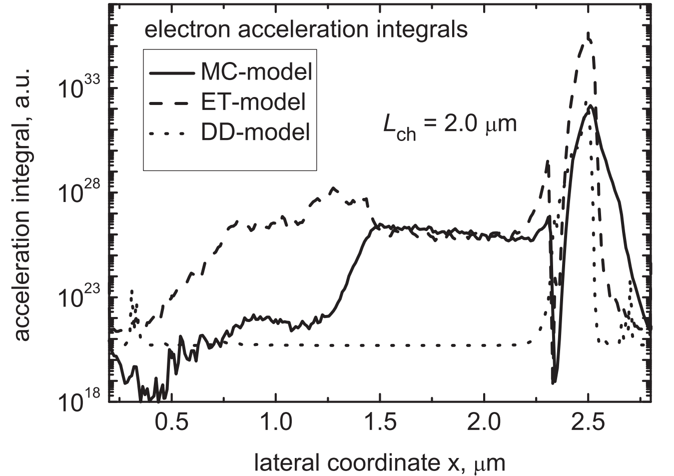

Fig. 4. The electron acceleration integral calculated with with MC-, ET-, and DD-based versions of our HCD model for the case of $L_{\rm ch} = 2.0\mu$m.

situated outside the channel, between the drain end of the gate and the drain. In contrast, hole-induced $N_{\rm it}$ is shifted toward the source and the device is more sensitive with respect to this damage. It is important to emphasize that the model is able to represent HCD for different channel lengths using the same

set of physically meaningful parameters. For instance, we used established values of characteristics describing the Si-H bond energetics [3], the Keldysh-like reaction cross section of the bond dissociation process [2], etc.

In this work we evaluate the carrier DF using three different methods. In the first approach, the DF is obtained by solving the BTE with the Monte-Carlo method. In the second version, only the average energy is taken from the Monte-Carlo solution in order to emulate the solution of an energy transport model. This energy profile $\langle E\rangle(x)$ is then used to approximate the carrier DF as a function of position as it is normally done in energy transport based physical models [18] $f(E) = A\,\exp[-E/\langle E\rangle]$. Here A is a normalization constant. Finally, in the third variant, we retain only the electric field from the Monte-Carlo solution. Using this field profile we obtain the average carrier energy as [14]: $\langle E\rangle = 3kT_{\mathrm{L}}/2 + q\tau_{\mathrm{E}}\mu F^2$, where k is the Boltzmann constant, T_{L} the lattice temperature, q the elementary charge, τ_{E} the energy relaxation time, μ the carrier mobility, and F the electric field. Note that in order to eliminate a possible origin of discrepancy related to different device simulators we performed all the calculations within MONJU.

IV. Results and discussion

The electron AIs computed within the MC-, ET- and DD-based models are plotted in Figs. 2–4 (note that all the findings are similar for the hole acceleration integral). The driving force of the degradation in the DD-based model is the electric field. However, the DF follows the electric field with a certain delay [19]. As a result, the maximum of the MC-based AI is shifted towards the drain with respect to the result of the drift-diffusion scheme. As we demonstrated e.g. in [11] starting from source to drain first the maximum of the carrier average energy appears followed by the electric field peak and finally the maximum of the AI when calculated with the Monte-Carlo method. In Figs. 2–4 the maxima of corresponding acceleration integrals are just in this order.

The N_{it} profiles calculated employing different transport schemes also confirm this behavior, see Figs. 5–7. The interface state density evaluated with the ET-based model spuriously overestimates the damage as compared to DD and MC schemes. Such a trend was expected based on our hot-carrier tunneling studies [18] where the tunneling process was also overestimated when the DF was simulated employing the ET scheme. As a result, the linear drain current degradation predicted by the ET-based model is much stronger than those obtained employing the MC DD approach (Figs. 8–9). Finally, the DD-based model predicts ΔI_{dlin} close to the result obtained by the MC-based model for $L_{\mathrm{ch}} = 1.2$ and $2.0\mu\mathrm{m}$ but totally fails for $L_{\mathrm{ch}} = 0.5\mu\mathrm{m}$.

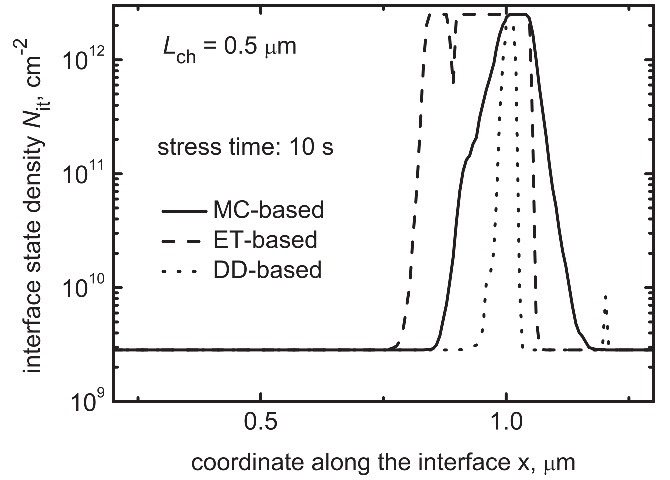

Fig. 5. The linear drain current degradation: experiment vs. simulations. The case of $L_{\mathrm{ch}} = 0.5\mu\mathrm{m}$.

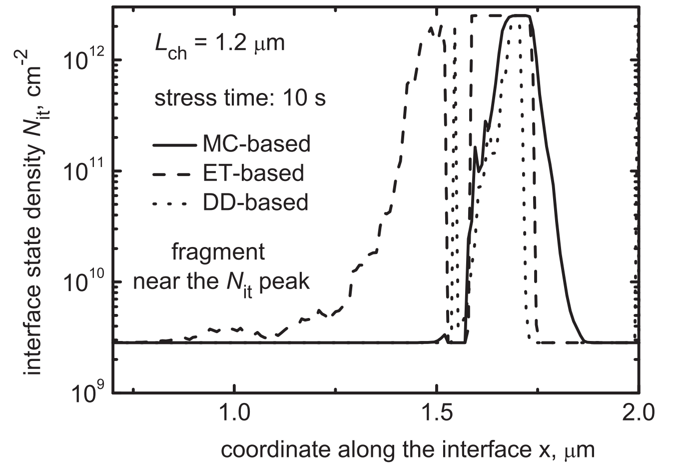

Fig. 6. The simulated $N_{\mathrm{it}}(x)$ profiles obtained with MC-, ET-, and DD-based versions of our HCD model for the case of $L_{\mathrm{ch}} = 1.2\mu\mathrm{m}$.

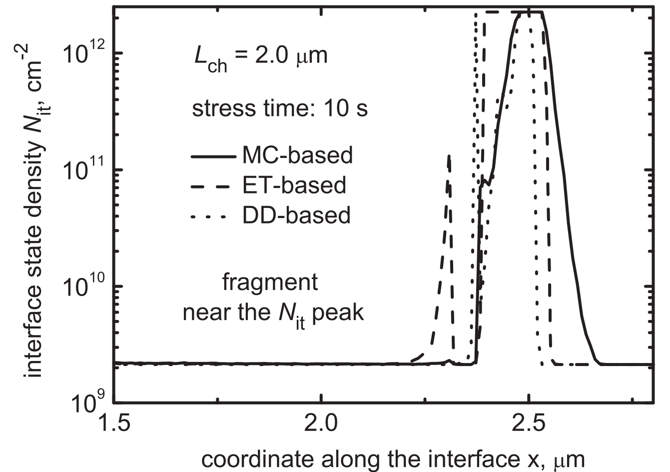

Fig. 7. The simulated $N_{\mathrm{it}}(x)$ profiles obtained with MC-, ET-, and DD-based versions of our HCD model for the case of $L_{\mathrm{ch}} = 2.0\mu\mathrm{m}$.

V. Conclusion

We have carried out a comparison between different versions of our physics-based model for hot-carrier degradation. These versions differ only in the realization of the carrier transport module. Namely, we employed Monte-Carlo, energy transport and drift-diffusion schemes for the solution of the Boltzmann transport equation. The comparison demonstrates that the ET-based model drastically overestimates the degradation while the DD-based version provides more adequate results for $L_{\mathrm{ch}} = 1.2, 2.0\mu\mathrm{m}$ but totally fails at $L_{\mathrm{ch}} = 0.5\mu\mathrm{m}$. Our MC-based model was thoroughly calibrated and able to represent the HCD in devices with different channel lengths

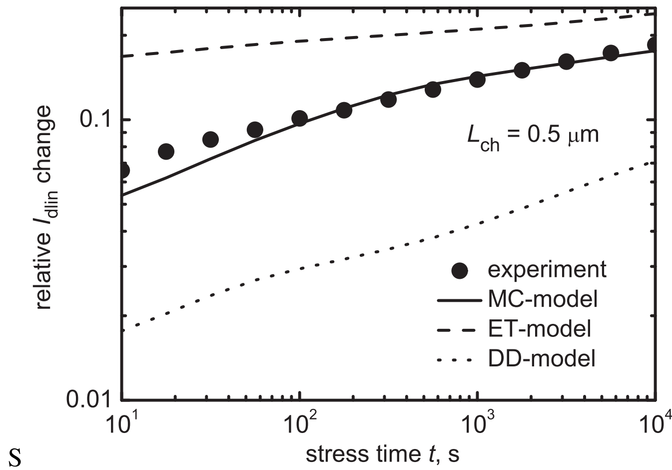

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Fig. 8. The linear drain current degradation: experiment vs. simulations. The case of $L_{\rm ch} = 0.5\mu{\rm m}$.

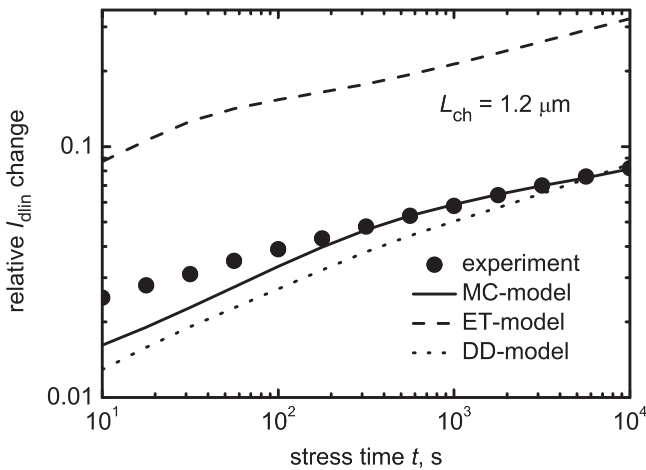

Fig. 9. The linear drain current degradation: experiment vs. simulations. The case of $L_{\rm ch} = 1.2\mu{\rm m}$.

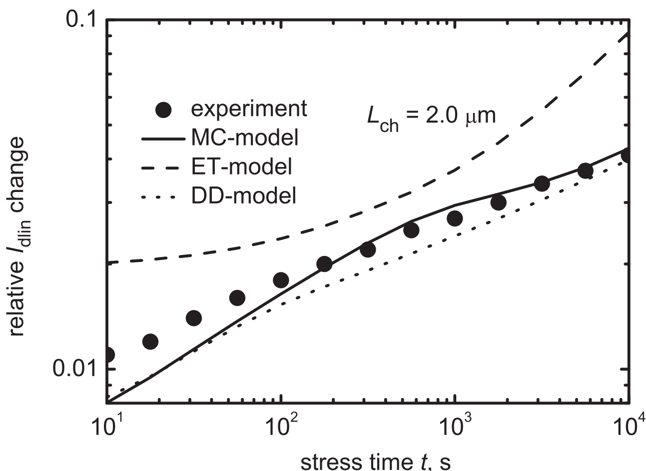

Fig. 10. The linear drain current degradation: experiment vs. simulations. The case of $L_{\rm ch} = 2.0\mu{\rm m}$.

operating with the physically reasonable set of parameters. These considerations suggest that simplified treatments of carrier transport with ET and DD schemes are not suitable for proper modeling of hot-carrier degradation.

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