

Simulation Study: the Effect of Random Dopants and Random Traps on Hot-Carrier Degradation in nFinFETs

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Abstract

We present a physics-based approach to modeling the effect of random dopants (RDs) and random traps (RTs) on hot-carrier degradation (HCD) in FinFETs. For each combination of stress voltages and stress time we generate 40,000 different samples with each of them having a unique configuration of RTs and RDs. Our analysis shows that at higher stress voltages device lifetime obeys bimodal normal distribution, while at conditions close to the operating regime the distribution has a significantly different shape. This suggests that accurate modeling of device lifetime should be based on a full statistical description of HCD.

1. Introduction

Hot-carrier degradation (HCD) has recently been reported as one of the most severe degradation phenomena in the most advanced fin field-effect-transistor (FinFET) nodes [1]. Ultra-scaled FETs contain just a handful of dopants which are randomly placed in the device and interface traps generated by hot-carrier stress are also stochastically distributed over the Si/dielectric interface. The impact of random dopants (RDs) results in variability of parameters of fresh devices while the random traps (RTs) lead to time dependent variability [2]. Although HCD induced variability is of great importance, existing models either do not consider the effects of both RDs and RTs on HCD [3-5] or perform stochastic modeling of HCD based on simplified approaches. Thus, Bottini *et al.* [6] model HCD variability by considering only the single-carrier (SC) mechanism of Si-H bond rupture and the multiple-carrier (MC) process is ignored, but in miniaturized transistors just the MC-process governs HCD and determines device lifetime [7-9].

We present a physics-based framework for stochastic modeling of HCD in n-channel FinFETs which takes into account both SC- and MC-mechanisms. In our previous publications [4, 5] we already carried out a statistical analysis of the impact of RDs on HCD. However, the impact of RTs was not addressed and therefore in this work we extend our approach and capture the cumulative impact of both RDs and RTs.

2. The Modeling Framework

This framework is based on our HCD model which captures the physical picture behind this parasitic phenomenon [10-12]: it evaluates the bond-breakage rates based on the carrier energy distribution function (DF); such DFs are obtained by solving the Boltzmann transport equation (BTE). The model was verified to cover relative changes in the linear drain current $\Delta I_{d,lin}$ vs. stress time t in nFinFETs with the channel length of 28 nm, operating voltage $V_{dd}=0.9$ V and a SiO₂/HfO₂ high-k stack with EOT=1.2 nm (Fig. 1). This realization of the model captures average experimental traces $\Delta I_{d,lin}(t)$ and parameterizes interface traps using the continuous concentration N_{it} . This model version is called “deterministic” and the corresponding results “nominal”.

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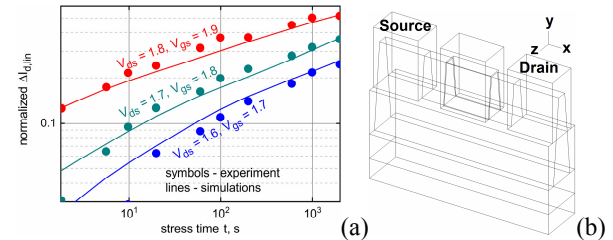


Fig. 1. (a) Experimental and simulated (with the deterministic version of our HCD model) normalized changes of the linear drain current with time, $\Delta I_{d,lin}(t)$ [12]. (b) A sketch of the FinFET.

Using the topology of the initial device (obtained from the Sentaurus Process simulator) with the continuous doping concentration as a template we generated a set of 200 samples with individual RD configurations. For each particular RD configuration we solved the BTE to obtain carrier DFs and continuous N_{it} concentrations. Then, we generated 200 different configurations of RTs based on a certain continuous N_{it} profile. Overall, for a fixed combination of V_{ds} , V_{gs} and t , 40,000 samples were generated.

3. Results and Discussion

All calculations were performed for $V_{ds}=1.7$ V, $V_{gs}=1.8$ V; $V_{ds}=1.8$ V, $V_{gs}=1.9$ V; and $V_{gs}=V_{ds}=1.0$ V (close to V_{dd}). To check the impact of RTs on the device characteristics, we calculated sets of $\Delta I_{d,lin}(t)$ traces (Fig. 2) and probit plots for the linear drain current $I_{d,lin}$ (Fig. 3). Fig. 3 shows that the currents in degraded devices are normally distributed and the distributions become broader with stress times. The $\Delta I_{d,lin}(t)$ curves in devices with varied RTs also have broad distributions with the corresponding mean values lower than those obtained for the nominal device, Fig. 2. As for device lifetimes (Fig.4), we can conclude that they are approximately normally distributed (with significant deviations visible at $V_{gs}=V_{ds}=1.0$ V).

Electron DFs calculated for different RD configurations are depicted in Fig. 5. The average DFs have lower values than the nominal ones and this tendency is especially pro-

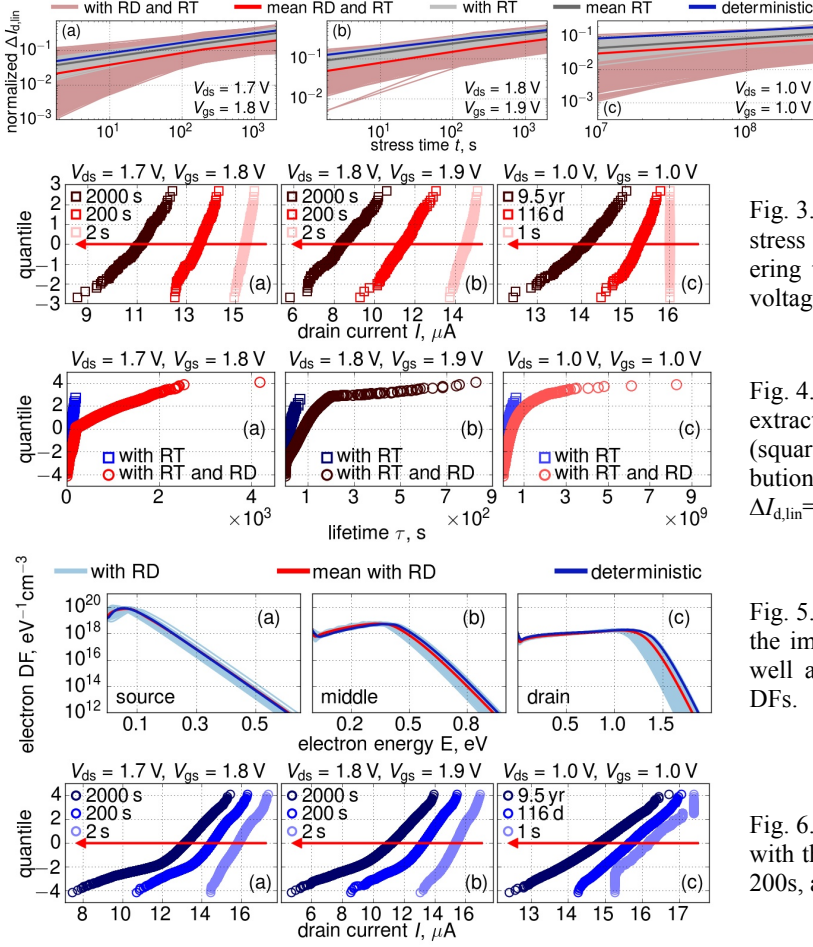


Fig. 2. The impact of RTs and RDs on $\Delta I_{d,lin}(t)$ changes. Grey curves represent $\Delta I_{d,lin}(t)$ dependences calculated with the impact of RTs only.

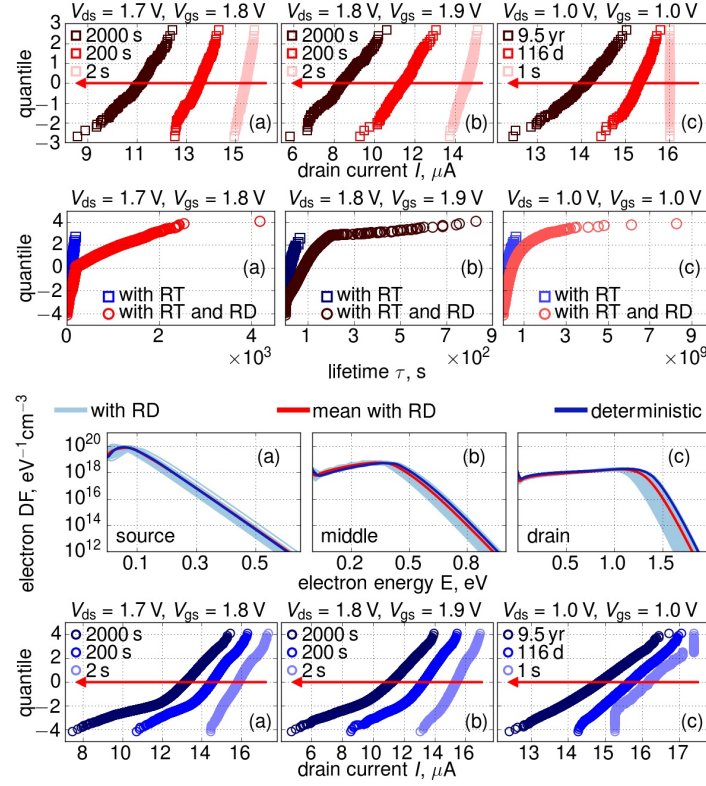


Fig. 3. Probit plots of $I_{d,lin}$ distributions for three stress times steps (2s, 200s, and 2ks) calculated considering the impact of RTs for all combinations of stress voltages.

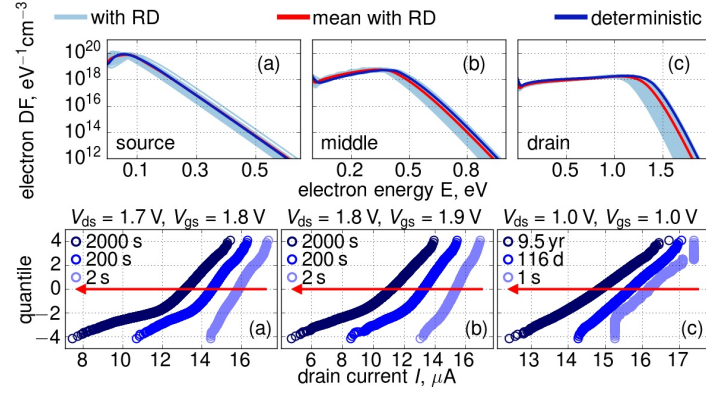


Fig. 4. Device lifetime distributions as probit plots extracted obtained considering the RT impact only (square symbols) and the mixture of RT and RD contributions (circles). Lifetimes are extracted based on the $\Delta I_{d,lin}=10\%$ criterion.

Fig. 5. Ensembles of electron DFs computed with the impact of RD for the source, channel, and drain as well as the average (over the ensemble) and nominal DFs.

Fig. 6. Probit plots for $I_{d,lin}$ distributions calculated with the impacts of RDs and RTs for stress times of 2s, 200s, and 2ks.

nounced near the drain where HCD is strongest, i.e. the impact of RDs weakens HCD. Fig. 6 summarizes quantile plots for $I_{d,lin}$ distributions calculated with the impacts of RTs and RDs and confirms this trend. Fig. 6 also shows that probit plots obtained with the impact of RDs spread over wider ranges. The distribution of $\Delta I_{d,lin}$ changes obtained with the cumulative impact of RDs and RTs is much broader than the distribution computed with the RT impact only. The $\langle \Delta I_{d,lin}(t) \rangle$ dependence (calculated with RDs and RTs) has lower values than that extracted from the set with varied RTs. As a consequence of the interplay between RT and RD impacts, the $\Delta I_{d,lin}(t)$ traces have lower values than the values predicted by the deterministic model (Fig. 2).

From the probit plots for device lifetimes (Fig. 4) we can see that in the case of higher stress voltages RTs and RDs result in two different slopes of the bimodal normal distribution. The steeper fragment visible at shorter lifetimes stems from the impact of RTs and qualitatively corresponds to the probit plot calculated with the RT contribution only, while at longer stress times the distribution is determined by the RD impact. It is important to emphasize that for $V_{gs}=V_{ds}=1.0V$ the distribution has a different shape. This bimodal distribution is consistent with experimental data recently reported by imec [13].

4. Conclusions

We carried out statistical modeling of HCD which captures the effect of both RTs and RDs. To achieve this goal, we employed 40,000 device realizations where each of

them has a unique configuration of RTs and RDs. It has been shown that both RTs and RDs broaden the ensemble of $\Delta I_{d,lin}(t)$ traces, thereby leading to average $\Delta I_{d,lin}$ values lower than those calculated without the effect of RTs and RDs. Finally, we showed that at higher stress voltage RTs and RDs lead to bimodal normal lifetime distributions, while at V_{dd} this distribution is significantly different. We therefore conclude that accurate extraction of device lifetime in the operating regime requires statistical treatment of HCD.

Acknowledgements

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References

- [1] A. Rahman *et al.*, IRPS (2018) 6F.4–1–6F.4–6.
- [2] B. Kaczer *et al.*, IRPS (2015) 3B.5.1–3B.5.6.
- [3] C. Liu *et al.*, IEDM (2014) 34.6.1–34.6.4.
- [4] A. Makarov *et al.*, IRPS (2019) 6C.3.1–6C.3.6.
- [5] A. Makarov *et al.*, IEEE EDL (2019), in press.
- [6] R. Bottini *et al.*, IRPS (2018) 6E.7–1–6E.7–6.
- [7] W. McMahon *et al.*, IEEE Trans. Nanotech. **2** (2003) 33–38.
- [8] A. Bravaix *et al.*, IRPS (2009) 531–536.
- [9] Y. Randriamihaja *et al.*, IRPS (2013) 1–5.
- [10] M. Bina *et al.*, IEEE TED (2014) **61**, 3103–3110.
- [11] S. Tyaginov *et al.*, IEEE EDL (2016) **37**, 84–87.
- [12] A. Makarov *et al.*, IEDM (2017) 13.1.1–13.1.4.
- [13] E. Bury *et al.*, IRPS (2019), in press.