3D TCAD Statistical Analysis of Transient Charging in BTI Degradation of Nanoscale MOSFETs

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Abstract— We present a comprehensive 3D statistical simulation analysis of transient charging during BTI degradation in nanoscale MOSFETs . We study the impact of several variability sources affecting the trap capture time constants. Our simulation results identify the activation energy involved in the multi-phonon capture process as major parameter responsible for BTI time constants variability. Our findings highlight the importance of further multiscale investigation involving experimental characterization, mesoscopic TCAD modeling and microscopic ab-initio computations.

Keywords—Reliability; Variability; RTN; NBTI; Device Modeling; Nanoscale MOSFETs.

I. INTRODUCTION

Degradation during the operational lifetime of MOSFETs is becoming a major reliability threat to the continuation of CMOS scaling [1]. In particular, the gate oxide wear-out plays the main role in determining the reliability performance of contemporary CMOS transistors. [2-4]. Recently, а fundamental paradigm shift in understanding MOSFET operational instabilities [5-7] has identified the discrete charge trapping/detrapping into the gate oxide as unique phenomenon underlying random telegraphic noise (RTN) [8], biased temperature instability (BTI) [6,9] and trap-assisted tunneling (TAT) gate leakage [10,11]. Besides, statistical variability (SV) due to random dopant fluctuations (RDF) has been shown to dramatically affect the performance and the reliability figures of merit of nanoscale transistors [12]. In Fig.1 we sketch the behavior of a typical BTI-charging trace for a nanoscale MOSFET, highlighting that SV occurs on both the vertical axes (through the variations induced on the threshold voltage shift amplitude ΔV_T) and the horizontal axes (through the variations induced on the capture time constants). On one hand, several experimental and modeling studies [7-9] have confirmed that the RDF-induced percolative conduction in the channel (Fig.2a, 2b) gives rise to an exponential distribution of threshold voltage shifts associated to a single trapped charge (Fig.2c). On the other hand, the understanding and modeling of capture time constants variability is, instead, more complicated and still object of intensive research [5,13]. Many factors can indeed affect the time constants behavior: (i) the non-uniform potential in the channel [14], (ii) the trap position and its energy level in

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Fig.1 Schematic representation of BTI charging in nanoscale MOSFET devices, highlighting the two components affected by device-to-device statistical variability.

the oxide band-gap [9], (iii) the variations in the capture properties associated to each different type of defects in the amorphous gate oxide [15].

In this paper we present a comprehensive 3D statistical simulation analysis of transient charging in BTI degradation of nanoscale MOSFETs, focusing our attention on several variability sources affecting the trap capture time constants. Our results are crucial for establishing a microscopic understanding of BTI and for suggesting a direction for further synoptic investigations linking the joined efforts of experimental characterization [6], mesoscopic TCAD modeling [5,9] and microscopic ab-initio computations [15].

II. SIMULATION METHODOLOGY

We performed 3D simulations of well-scaled MOSFET devices using the GSS 'atomistic' simulator GARAND featuring a drift-diffusion approximation with density gradient quantum corrections [16]. Figs.2a and 2b show the electron concentration in the presence of a random configuration of dopants. The oxide traps leading to BTI are modelled by assigning three positional coordinates (x_T,y_T,z_T), one energy level ($E_{T,0}$) and a capture cross-section (σ_0) for each trap. Simulation of BTI transients is achieved within a Kinetic Monte Carlo (KMC) loop, as shown in Fig.3. After solving the 3D electrostatics and current continuity equation (at $V_G=1V$, $V_D=0.05V$), the average capture time $<\tau_c>_i$ for each single i-th trap is computed integrating the tunnelling gate current density



Fig.2 Impact of a trapped charge on the percolative conduction of a 25nm MOSFET:(a) Empty trap; (b) Filled trap; (c) 3D simulations of 1000 atomistic devices confirm that single trap ΔV_T is exponentially distributed due to RDF. The exponential behaviour is lost when adopting a uniform doping.



Fig.3 Simulation procedure developed for the dynamic charge trapping under BTI conditions.

that reaches the trap (WKB approximation) over an area equal to the trap cross-section σ [17]:

$$\tau_c = q / \int_{\sigma} J(x, y) dx dy \qquad \sigma = \sigma_0 \exp(-E_A / kT) \quad (1)$$

The exponential factor in the trap cross-section takes into account the activation energy of the trapping process, the latter confirmed by many experimental works to be an inelastic multiphonon assisted charge transfer from channel to oxide trap [5]. Please note that, in our model, the dependence of the activation energy from the electric field [18,19] and corrective factors due to Coulomb blockade effects [20] are neglected. Once the average capture time is computed for each trap, the actual capture times are randomly extracted from exponential distributions of average value $<\tau_c>_i$. Based on these constants, a KMC-engine chooses the trap to be filled and the dynamic simulation time is increased by the extracted $\tau_{c,i}$. The loop is repeated until all traps are filled. In this work we are not considering the emission mechanism, being a minor correction at high applied gate voltages [5]. In the following, we will analyse how the several parameters of this trapping model affect the dispersion of time constants and, in turn, the transient BTI dynamics.

III. RESULTS AND DISCUSSION

We started our investigation with a scaling analysis of BTI charging. In order to allow a fast simulation of very large devices, we have used the KMC procedure in Fig.3, but without solving the electrostatics and assuming that the single step ΔV_T are exponentially distributed, with average computed through the charge sheet approximation as done in [21]. This analytical approach is well founded because the statistical interaction of multiple trapped charges is negligible as shown by both experimental results [22] and full-3D 'atomistic' simulations [23]. Under these circumstances the ΔV_T distribution due to many trapped charges can be obtained by successive convolutions of the ΔV_T distribution due to single trapped charge and the number of trapped charges in the oxide follow a Poisson distribution at any BTI stressing time [23]. In a similar way, the average time constant of each trap is not computed from 3D electrostatics, but randomly assigned from



Fig.4 Simulated BTI transients with the simplified KMC approach of ref. [18] for a 35x90nm (blue) and 280x720nm (green) devices. The $<\tau_c>_i$ are randomly distributed in $[10^{-2}-10^2s]$ (Top) and $[10^{-5}-10^5s]$ (Bottom). Red dashed line is the average transient.



Fig.5 As Fig.4 (35x90nm device) but the $\langle \tau_c \rangle_i$ are randomly distributed in the range $[10^{-5} \cdot 10^8 \text{s}]$ to fit the experimental data of [21] yellow dots).

a log-uniform distribution [24]. The analytical simulation results reported in Fig.4 clearly shows that scaling down the device size (with fixed $\langle \tau_c \rangle$ variability range) increases the variability of BTI charging along the vertical axes, but does not modify the slope of the average charging curve. In the same figure we show that a change in the average charging slope can be obtained only by modifying the range of $\langle \tau_c \rangle$ variability. In particular, Fig.5 shows that, in order to fit the experimental BTI-charging data reported in [21], $\langle \tau_c \rangle$ needs to span a 13-orders of magnitude variability range.

The remaining task is to identify which of the parameters of our physics-based model in eq.(1) can hold up the variability of $<\tau_c>$. In order to address this issue we have adopted the full-3D procedure in Fig.3. Fig.6 shows that RDF is not sufficient alone to explain large variations of time constants in respect to what is already done by the non-uniform electrostatics, as also noted in [14]. Simultaneously the dispersion in the trap energy level $E_{T,0}$ has very low impact on $<\tau_c>$ variability (Fig.7). Fig.8 shows that the variability of the cross-section pre-factor σ_0 may play a non-negligible role, although it becomes un-physical to justify more than 3-4 orders of magnitude of variations on σ_0 . Fig.9 shows, instead, that a variation of few hundreds meV in the trapping activation energy E_A can perfectly give reason to



Fig.6 Simulated BTI transients with the full 3D TCAD procedure of Fig.3. Only the x_T , y_T variability is considered for the Uniform case. Atomistic doping is added also for the RDF case. Solid lines=average BTI.



Fig.7 As Fig.6 but with the additional degree of freedom on the trap energy level variability.

the $\langle \tau_c \rangle$ dispersion necessary to fit the experimental charging slope. This E_A variations can have a root cause in the dependence of the trapping process from the local electric field [5] or can lie on the local atomic configuration of the trapping site in the inherently disordered amorphous gate oxide [15]. Only the combined efforts of experimental characterization of charging transients (and their dispersion with device size scaling), mesoscopic TCAD modelling, and ab-initio molecular dynamics simulations can push forward the understanding of BTI in decananmometer MOSFET devices.

IV. CONCLUSIONS

In this paper we have presented a comprehensive 3D statistical simulation analysis of transient charging during BTI degradation in nanoscale MOSFETs. We have analysed the impact of several source of variability on the trap capture time constants. Our results showed that the activation energy involved in the multi-phonon charge capture process plays the major role in determining the variability of BTI single events time constants. These findings suggest a direction for further multiscale investigations linking the joined efforts of experimental characterization [6], mesoscopic TCAD modeling [5,9] and microscopic ab-initio computations [15].



Fig.8 As Fig.6 but with the additional degree of freedom on the trap capture cross-section variability.

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Fig.9 As Fig.6 but with the additional degree of freedom on the charge trapping activation energy variability.

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