A Rigorous Study of Measurement Techniques for Negative Bias Temperature Instability

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***Abstract*— The active research conducted in the last couple of years demonstrates that negative bias temperature instability (NBTI) is one of the most serious reliability concerns for highly scaled pMOSFETs. As a fundamental prerequisite for a proper understanding of the phenomenon, accurate measurements are indispensable. Unfortunately, due to the nearly instantaneous relaxation of the degradation once the stressing conditions are removed, an accurate assessment of the real degradation is still extremely challenging. Consequently, rather then interrupting the stress in order to measure the degradation, alternative measurement techniques, such as the on-the-fly methods, have been proposed which avoid stress interruption. However, these methods rely on rather simple compact models to translate the observed change in the linear drain current to a threshold voltage shift. As such, all methods have their own drawbacks which are rigorously assessed using a theoretical description of the problem.**

I. Introduction

When subjected to negative bias temperature stress, device parameters of pMOS transistors have been observed to degrade [1–3]. This degradation is commonly described by a shift of the drain current or threshold voltage as a function of stress time. Due to the extremely fast recovery which sets in as soon as the stressing conditions are removed, any accurate assessment of the real degradation is very challenging.

In order to cope with that serious problem, many different measurement techniques have been proposed so far, which fall into two different categories:

(i) Conventional measure/stress/measure (MSM) techniques, which have been optimized by minimizing the delay between removal of the stress and the first measurement point. In MSM techniques either the drain current around the threshold voltage [4] is recorded and mapped to ΔV_{th} using an initial $I_{\mathrm{D}}V_{\mathrm{G}}$ curve around ΔV_{th}, or a threshold current is enforced through the device [5], thereby directly measuring ΔV_{th}. Alternatively, complete $I_{\mathrm{D}}V_{\mathrm{G}}$ curves have been recorded using ultra-short pulses [6, 7].

(ii) On-the-fly (OTF) techniques monitor the degradation of the drain current in the linear regime, I_{Dlin}, directly under stress conditions, thereby avoiding any relaxation. Different variants have been put forward [2, 8–10] which are more or less straightforward to implement [10].

In order to link the observed degradation to possible underlying physical mechanisms, most commonly the creation of interface states and positive oxide charges [2, 3], a parametric relationship between the threshold-voltage shift/drain current and these charges is required. The most logical candidate is the shift of the threshold-voltage, because it is directly related to the effective density of interface states and oxide charges as

$$\Delta V_{\mathrm{th}}(t) = -\frac{\Delta Q_{\mathrm{it}}(t) + \Delta Q_{\mathrm{ot}}(t)}{C_{\mathrm{ox}}} \ . \tag{1}$$

The positive charge stored in the interface states $Q_{\mathrm{it}}(t)$ is given by $\mathrm{q}N_{\mathrm{it}}(t)f(V_{\mathrm{G}})$, where f denotes the occupancy of N_{it} depending on the gate (measurement) voltage V_{G}. By contrast, I_{Dlin} not only depends on V_{th} and thus on Q_{it} and Q_{ot}, but also on the effective mobility μ_{eff}, which is known to change during degradation [1, 9, 11]. As will be shown, this may make the interpretation of measurement results challenging.

It is thus important to realize that none of the available measurement techniques is able to directly measure the real degradation: while MSM techniques have to cope with unavoidable delays, OTF techniques may also suffer from the conversion of ΔI_{Dlin} to ΔV_{th}, which is conventionally justified [2, 9] using rather simple compact models. As such, the results given by these techniques have been reported to differ by more than an order of magnitude in extreme cases [3, 9]. Although this is commonly attributed to the delay inherent in MSM techniques [3], we will show that this issue is more involved by conducting a thorough theoretical study using a numerical device simulator enhanced by appropriate reliability models.

II. Methodology

A comparison of MSM and OTF results is given in Fig. 1 for a typical IMEC device [4]: While the MSM technique can estimate the true degradation only via extrapolation (we use our technique [12, 13] based on the universality of NBTI degradation [12, 14]), the ΔV_{th} values predicted by the simplest OTF method do not fit the detailed relaxation data very well, regardless of any extrapolation uncertainties.

In order to study this discrepancy we turn the problem around: we place a certain predefined amount of ΔQ_{it} and ΔQ_{ot} at the interface of a pMOS and numerically simulate the drain current observed in the various techniques. The simulated drain current is then processed analogously to the measurement data and converted into ΔV_{th}. We then compare whether the true ΔV_{th} given by the predefined charges agrees with what is observed in the measurements. Furthermore, this approach allows us to study the sensitivity of the extracted ΔV_{th} to the measurement setup. For our simulations we employ a suitably extended version of our numerical device simulator Minimos-NT [15]. We include accurate models for the interface state dynamics (SRH) with a realistic density-of-states distribution [12, 16] and the mobility variation due to Coulomb scattering induced by interface states [17]. All simulations are based on a numerical device description carefully calibrated to measured $I_{\mathrm{D}}V_{\mathrm{G}}$ curves.

The time evolution of the interface and oxide charges is extracted from our measurement data and described analytically as a function of the net stress time t_{s} and the recovery time t_{r}. Oxide charges are assumed to recover universally [2, 14, 18] and are modeled by

$$Q_{\mathrm{ot}}(t_{\mathrm{s}}, t_{\mathrm{r}}) = A \log\Big(1 + \frac{t_{\mathrm{s}}}{\tau}\Big) r(t_{\mathrm{r}}/t_{\mathrm{s}}) \tag{2}$$

with the universal relaxation function

$$r(\xi) = \frac{1}{1 + B\xi^{\beta_{\mathrm{r}}}} \tag{3}$$

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and the parameter values $\tau \approx 2\,\text{ns}$, $B \approx 3$, and $\beta_\text{r} \approx 0.18$. We remark that these values are determined for relaxation at $V_\text{G} \approx V_\text{th}$ and vary for other bias conditions.

The interface charges, on the other hand, are assumed to be permanent [2, 18] (on the time-scale of the measurements) and are assumed to follow a power-law

$$N_\text{it}(t_\text{s}) = A_\text{p} t_\text{s}^{n_\text{p}} \; , \tag{4}$$

with $n_\text{p} \approx 0.3$. Note that the actual charge stored in these interface states depends on the position of the Fermi-level (and thus the gate voltage) via the density-of-states. For our choice of parameters [16] we found that during stress all interface states are positively charged while during relaxation (measurement around V_th) the occupancy goes down to $\sim$75%.

We also remark that the widely used reaction-diffusion model [1, 3], given by $Q_\text{ot} \approx 0$, $Q_\text{it} = At_\text{s}^n r(t_\text{r}/t_\text{s})$, $n = 1/6$, $B = 1$, and $\beta_\text{r} = 1/2$, is unable to capture any relaxation data known to us [12].

Finally, recall that the association of the fast/universally-recovering component with trapped holes and the slow/permanent component with interface states is still under heated debate [2, 19]. Nevertheless, the choice made in this analysis is of little consequence to the basic results. The idea was to include a component that has a Fermi-level/surface-potential dependent occupancy, while the Fermi-level dependence of the trapped holes for recovery at $V_\text{G} = V_\text{th}$ is empirically described by the universal relaxation function (3).

In the following, the measurement methods discussed in this work are summarized. We also highlight potential distortions due to often unappreciated physical effects like mobility variations and interface state dynamics.

A. MSM Methods

First, we use the method suggested in [4] which records several relaxation phases after exponentially growing stress intervals. As such, a maximum amount of information on a single device in a single measurement cycle is gathered. The recorded drain current around V_th is then converted into ΔV_th using an initial (narrow) $I_\text{D}V_\text{G}$ curve. Using the method developed in [13], a fast component R on top of a permanent component P is extracted and mapped to ΔQ_ot and ΔQ_it using the previously stated prescription.

In addition to this single-point I_D method, we calculate fast (1 μs) $I_\text{D}V_\text{G}$ curves for the extraction of ΔV_th using two constant current criteria. We remark that the relaxation predicted by our model is accurate only when switching the bias from the stress-level to $V_\text{G} = V_\text{th}$, and the estimates obtained using this method must be taken with care.

B. OTF Methods

The three OTF extrapolation methods investigated here are based on a simple compact model (or variants thereof) valid in the linear regime under strong inversion [20] [1]

$$I_\text{D} = \frac{\beta V_\text{D}(V_\text{G} - V_\text{th} - \frac{1}{2}V_\text{D})}{1 + \theta(V_\text{G} - V_\text{th} - \frac{1}{2}V_\text{D})} \; . \tag{5}$$

Curiously, the fact that the threshold voltage V_th used in expressions like (5) is the purely empirical *extrapolated threshold voltage* [20] rather than the 'correct physics-based' threshold voltage one obtains from the solution of the Poisson equation, is rarely appreciated [10]. This implies that changes in the extrapolated threshold voltage are not necessarily related in a 1:1 manner to additional charges at the interface/oxide, also due to hidden correlations in the parameters V_th, θ, and β [21].

[1] We use the conventional nMOS sign convention in all formulas, with the sign change for pMOS devices being understood.

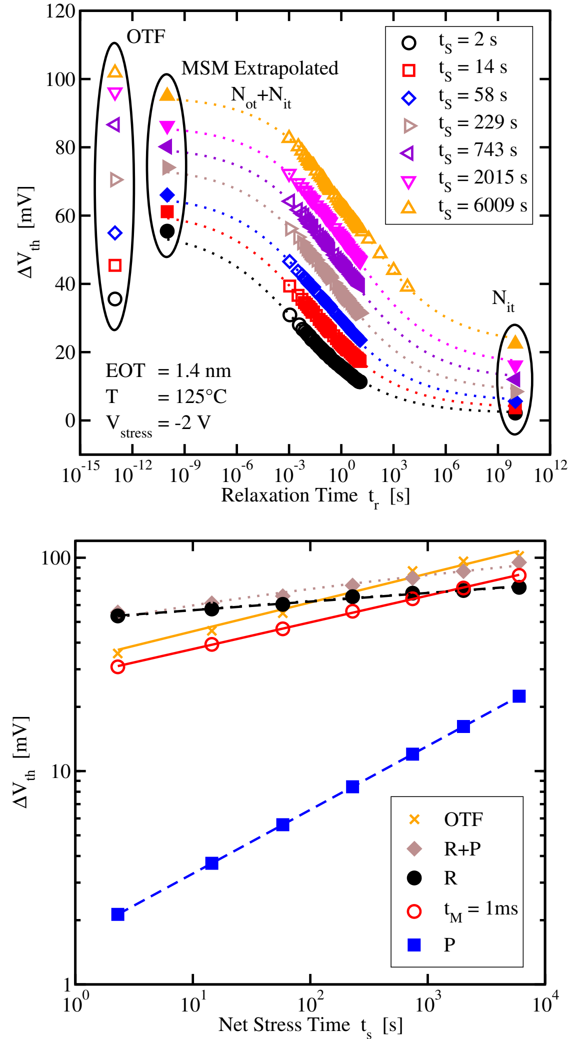


Fig. 1. Comparison of measured MSM and OTF1 data (open symbols). **Top**: The recorded detailed relaxation sequence allows one to reconstruct the full NBTI degradation (closed symbols and lines) by identifying a universally relaxing component R which is observed on top of a permanent/slowly relaxing component P. The degradation observed in OTF1 measurements does not agree well with the relaxation data. **Bottom**: The extracted components R and P, the OTF1 data, and the MSM data with a delay of $t_\text{M} = 1\,\text{ms}$ as a function of the stress time. Clearly, the overall degradation $R + P$ is only in poor agreement with the OTF1 data.

The first and simplest OTF method we discuss (OTF1) assumes θ and V_D to be small and also neglects any change in the effective mobility μ_eff (and thus β) [1, 3]

$$\Delta V_\text{th}^{(1)} \approx \frac{I_\text{D} - I_\text{D0}}{I_\text{D0}}(V_\text{G} - V_\text{th0}) \; . \tag{6}$$

The OTF1 method has the advantage that it only requires the determination of the initial drain current in the linear regime under stress conditions. The neglect of the mobility change (β and θ) in the OTF1 method has motivated the proposal of the OTF2 method which is capable of monitoring a mobility variation by introducing

small perturbations of the stress voltage [2]

$$\Delta V_{\rm th}^{(2)} \approx \sum_n \frac{\dfrac{I_{\rm D}[n]}{g_{\rm m}[n]} - \dfrac{I_{\rm D}[n-1]}{g_{\rm m}[n-1]}}{1+2\theta(V_{\rm G}-V_{\rm th}[n]-\frac{1}{2}V_{\rm D})} \ . \tag{7}$$

However, OTF2 still neglects the temporal change of θ. Furthermore, the OTF2 technique requires the determination of a full initial $I_{\rm D}V_{\rm G}$ curve for the determination of θ. Thus, as an alternative one may use a variant suggested by Zhang and Chang [9] (OTF3):

$$\Delta V_{\rm th}^{(3)} \approx \sum_n \frac{I_{\rm D}[n]-I_{\rm D}[n-1]}{\frac{1}{2}(g_{\rm m}[n]+g_{\rm m}[n-1])} \ . \tag{8}$$

III. Possible Distortions

The analysis of measurement data often assumes that the change in the drain current is only caused by $\Delta V_{\rm th}$ due to oxide/interface charges. However, it has been pointed out [2, 9, 11] that mobility variations may impact the accuracy of the methods. This issue is commonly associated with OTF techniques, but a rigorous analysis has not been conducted so far. This will be done in the following, where we also demonstrate the impact of mobility variations on MSM techniques. In addition, the response of the interface states on rapidly changing gate voltages is discussed.

A. OTF Methods

To analyze the sensitivity of the extracted $\Delta V_{\rm th}$ to changes in the mobility we estimate the drain current in the linear region by a further simplified version of (5) ($\theta \approx 0$, $V_{\rm D} \ll V_{\rm G}$)

$$I_{\rm D} = \beta V_{\rm D}(V_{\rm G}-V_{\rm th}) \ . \tag{9}$$

According to OTF1, the change in the linear drain current is converted to a threshold-voltage shift using $\Delta V_{\rm th} = \Delta I_{\rm D}/\beta$. Since β is to first-order linearly proportional to $\mu_{\rm eff}$, according to (9), a change in $\mu_{\rm eff} = \mu_{\rm eff0} + \Delta\mu_{\rm eff}$ results in

$$\Delta I_{\rm D} = I_{\rm D0}\Delta\mu_{\rm eff}/\mu_{\rm eff0} \ . \tag{10}$$

Assuming that this shift $\Delta I_{\rm D}$ is *only* caused by mobility variations, a spurious shift in $\Delta V_{\rm th}$ is obtained as

$$\Delta V_{\rm th}^{\mu} = -\frac{\Delta\mu_{\rm eff}}{\mu_{\rm eff0}}(V_{\rm G}-V_{\rm th}) = -(V_{\rm G}-V_{\rm th})\frac{p}{100} \ , \tag{11}$$

with p being the mobility variation in percent. With $V_{\rm G} = 2\,{\rm V}$ and $V_{\rm th} \approx 0.25\,{\rm V}$ (fit to the linear part of the on-current), we obtain that the error in the extracted $\Delta V_{\rm th}$ equals $17.5\,{\rm mV}$ for each percent mobility error, rather much larger than previously anticipated [1]. As an example, for an error in the effective mobility of 3% [1], one obtains an error of about $50\,{\rm mV}$ in $\Delta V_{\rm th}$.

B. MSM Methods

By contrast, data obtained via the MSM technique is much less sensitive to mobility changes. This can be easily demonstrated starting from a simple compact model for the subthreshold current [20]

$$I_{\rm D} = A\mu_{\rm eff}\exp\Big(\frac{V_{\rm G}-V_{\rm th}}{\eta V_{\rm T}}\Big) \ . \tag{12}$$

Here, $V_{\rm T}$ is the thermal voltage $\mathrm{k_B}T/\mathrm{q}$. Although the current in the subthreshold regime is also proportional to the mobility change and, consequently, a change in the mobility results also in an equivalent change of $I_{\rm D}$ via (10), the drain current depends now *exponentially* on the threshold-voltage shift. Thus, by inverting (12) one obtains

$$\Delta V_{\rm th}^{\mu} = -\eta V_{\rm T}\log\Big(1+\frac{\Delta\mu_{\rm eff}}{\mu_{\rm eff0}}\Big) \approx -\eta V_{\rm T}\frac{\Delta\mu_{\rm eff}}{\mu_{\rm eff0}} \tag{13}$$

$$= -\eta V_{\rm T}\frac{p}{100} \ . \tag{14}$$

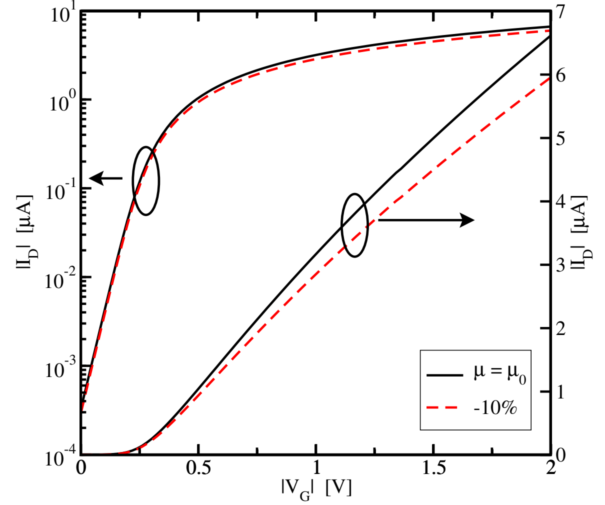


Fig. 2. Simulated $I_{\rm D}V_{\rm G}$ characteristics at $V_{\rm D} = -50\,{\rm mV}$ with nominal mobility values and a mobility degradation of about 10%. Clearly, the impact is largest in the linear regime.

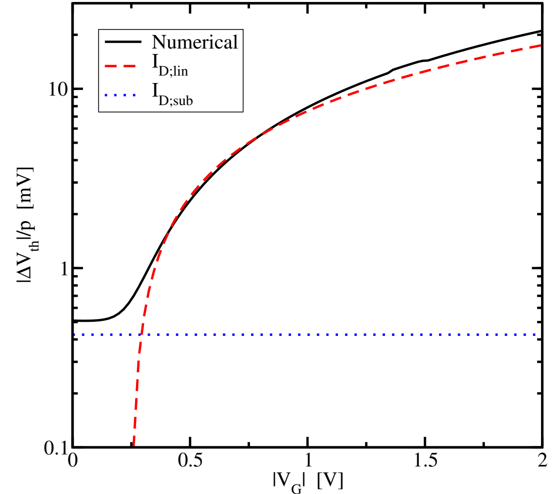


Fig. 3. The spurious threshold-voltage shift $\Delta V_{\rm th}^{\mu}$ per percent change in $\mu_{\rm eff}$ obtained from Fig. 2 by considering the difference in $V_{\rm G}$ at the same $I_{\rm D}$. With increasing $V_{\rm G}$ $\Delta V_{\rm th}^{\mu}$ increases. Also shown are the error estimates for the linear regime (11) (dashed lines) and the subthreshold regime (14) (dotted lines).

For the device under consideration $\eta \approx 1.14$ (subthreshold slope of about $68\,{\rm mV/dec}$ at room temperature), giving $\eta V_{\rm T} \approx 42\,{\rm mV}$ and finally a $420\,\mu{\rm V}$ error for each percent variation in the mobility. However, since the variation of the low-field mobility is expected to be larger than the high-field mobility [1, 9], for instance 10%, one obtains an error in $\Delta V_{\rm th}$ of about $5\,{\rm mV}$, which is about a factor of ten lower than the corresponding error in the OTF method. Interestingly, the mobility-variation-induced error of the MSM method depends linearly on temperature via $V_{\rm T}$, while the error of the OTF has only a weak temperature dependence via $V_{\rm th}$.

C. General Gate-Voltage Dependence

The previous two results clearly show that the impact of the mobility variation on the estimated threshold-voltage shift depends

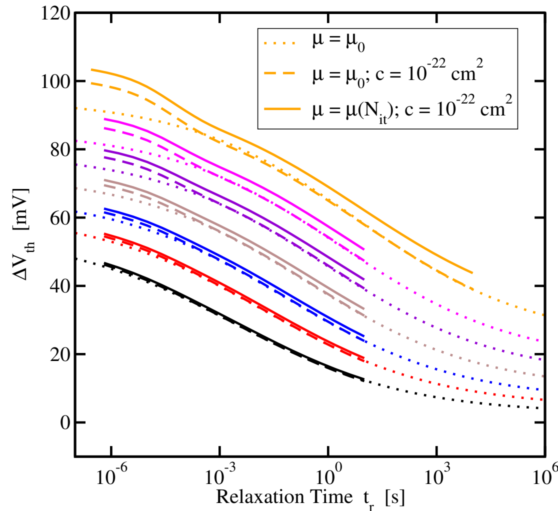
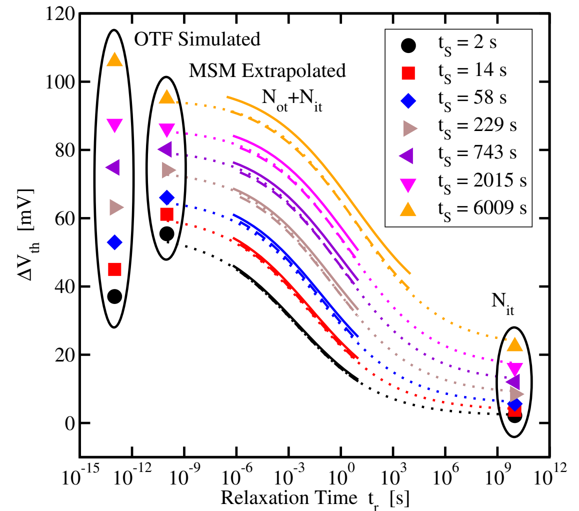


Fig. 4. Simulated impact of a 10% mobility variation and the dynamics of the interface state occupancy on the extracted ΔV_{th}. The same stress-times as in Fig. 1 are used. Since the mobility model used depends only on N_{it}, which is assumed to be permanent, the mobility variation causes a constant offset in each relaxation curve. Also, only for unusually small capture cross sections c in the order of $10^{-22}\,\mathrm{cm}^2$ initial distortions of ΔV_{th} can be observed.

on the operation mode of the transistor and thus on the applied gate voltage. Fig. 2 shows the change in the numerically simulated $I_{\mathrm{D}}V_{\mathrm{G}}$ characteristics caused by a 10% mobility degradation. Clearly, the impact is largest in the linear regime. The spurious threshold-voltage shift caused by this mobility variation is obtained by determining the difference in V_{G} at the same current I_{D}. For reasonable changes in the mobility, this spurious $\Delta V_{\mathrm{th}}^{\mu}$ depends linearly on the mobility variation. Fig. 3 shows $\Delta V_{\mathrm{th}}^{\mu}$ per percent mobility variation, p, as a function of gate bias. The smallest dependence of $\approx 500\,\mu\mathrm{V} \times p$ is obtained in the subthreshold regime (in that example $V_{\mathrm{G}} < 0.2\,\mathrm{V}$), where I_{D} perfectly follows (12). This value is in good agreement with the estimate (14). Consequently, in order to avoid mobility induced distortions of ΔV_{th}, measurements should be conducted with V_{G} safely in the exponential regime of I_{D}. For larger V_{G}, on the other hand, $\Delta V_{\mathrm{th}}^{\mu}$ rapidly increases in accordance with (11), which is also in good agreement with the full numerical result.

D. Response of Interface States

An issue particularly relevant for ultra-fast MSM measurements is the response of the interface states to a quickly changing gate voltage. One may argue that for measurements in the μs regime, the interface states may not react fast enough to the rapid drop in V_{G} and thus distort the response of I_{D} and consequently the estimated ΔV_{th} [22]. From a theoretical point of view, this response is described using SRH kinetics which is straight-forward to include in a numerical simulation. The time scales are determined by the capture cross sections, somewhat difficult to determine quantities [23]. In order to accurately reproduce charge-pumping measurements, capture cross sections in the order of $10^{-16}\,\mathrm{cm}^2$ are used in our simulator. Note, however, that values in the range $10^{-14}\ \ldots 10^{-18}\,\mathrm{cm}^2$ have been reported [23, 24]. Interestingly, an impact of interface state dynamics on the simulated I_{D} in the μs regime is only observed for unusually small capture cross sections in the order of $10^{-22}\,\mathrm{cm}^2$ (cf. Fig. 4). Such small capture cross sections can probably only be justified by assuming defects at a certain distance from the interface which require tunneling for charge exchange [25]. We remark that such a process, if occurring on top of the fast component R, would result in a visible hump in the relaxation of I_{D}, not present in any of the data available to us [26]. Thus, we prefer the notion that if such a process is relevant at all, it should naturally be part of the fast component R.



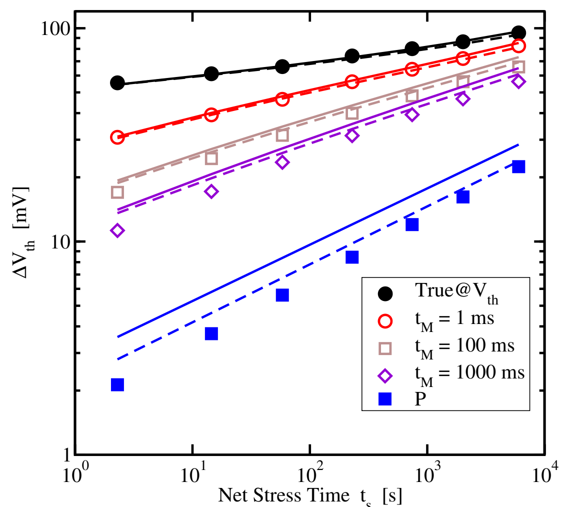


Fig. 5. Simulation of the measurement sequence given in Fig. 1, which exactly reproduces the measurement results used to extract N_{it} and N_{ot} without any serious distortion. **Top**: The extracted ΔV_{th} shift, with and without considering the mobility variation (solid and dashed lines), confirming that the extraction is only weakly dependent on the mobility variation. The dotted lines are a guide to the eye taken from Fig. 1. **Bottom**: The same simulation results as a function of the stress time. The simulation results (lines) agree very well with the measurement data (open symbols) and the extracted P and R components (closed symbols). A $4\,\mathrm{mV}$ error is introduced in the permanent component (N_{it}) when the 10% mobility degradation is considered.

IV. Results

In the following we introduce the analytic models for Q_{ot} and Q_{it} into the device simulator, re-simulate the various measurement sequences, and compare the extracted with the expected values.

A. MSM Methods

We begin with the MSM method used to originally extract the temporal evolution of Q_{ot} and Q_{it}. Quite convincingly, the simulation reproduces the relaxation data at $V_{\mathrm{G}} \approx V_{\mathrm{th}}$ and captures the trend

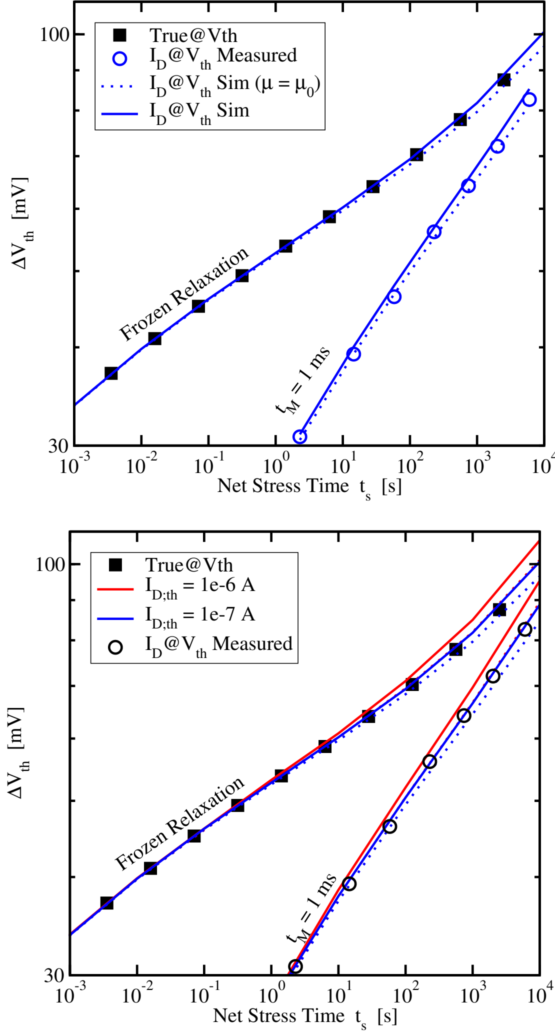


Fig. 6. The ideal no-delay MSM measurement exactly reproduces the true ΔV_{th}. In particular, the extracted ΔV_{th} is only weakly dependent on the mobility change (solid vs. dotted lines) and the extraction method. Shown are extractions from I_{D} at V_{th} (top) and from $I_{\mathrm{D}}V_{\mathrm{G}}$ curves with various $I_{\mathrm{D,th}}$ values (bottom). With increasing $I_{\mathrm{D,th}}$, a small additional error is visible due to the increased occupancy of N_{it}.

in the OTF1 data at $V_{\mathrm{G}} = -2\,\mathrm{V}$ (cf. Fig. 5). The extracted ΔV_{th} with zero delay (frozen relaxation) and neglected mobility changes agrees perfectly with the expected values given through Q_{ot} and Q_{it}. However, when the degradation of the mobility is considered (about 10% at $10^5\,\mathrm{s}$ [1]), an error of about $4\,\mathrm{mV}$ at $t_{\mathrm{s}} = 6000\,\mathrm{s}$ is observed. Since the mobility model used assumes only the permanent interface states to affect the mobility, no relaxation in this error is observed. Consequently, this error translates directly to the permanent component. In reality, also oxide charges located farther away from the interface will affect the mobility, so a slight change in this result is to be expected.

In addition to confirming the good accuracy of the MSM single-point method, the influence of the measurement delay is exactly reproduced. In particular, although strongly dependent on the measurement delay, the extracted ΔV_{th} is practically independent of the method used (conversion of $I_{\mathrm{D}}(V_{\mathrm{th}})$, see [4], various constant I_{D} criteria, ultra-fast pulses, etc.) and the stress-dependent change in the mobility (cf. Fig. 6).

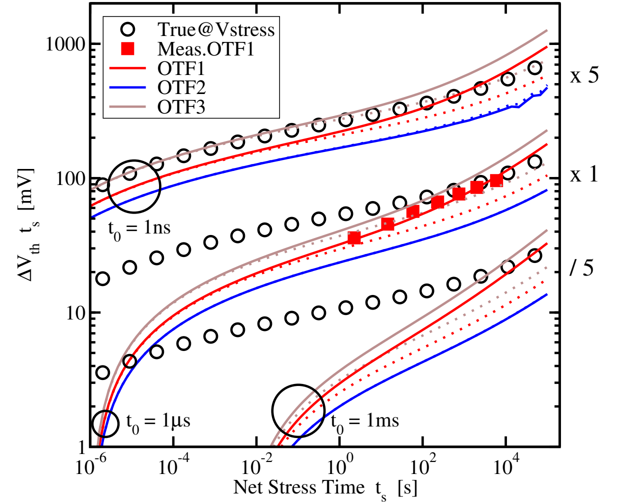


Fig. 7. Influence of the initial delay t_0 and the mobility change on OTF results. While all OTF methods are strongly affected by the delay of the initial measurement (data scaled by a factor of 5 for readability), only OTF2 is not affected when the full interface charge dependent mobility model is used (solid lines).

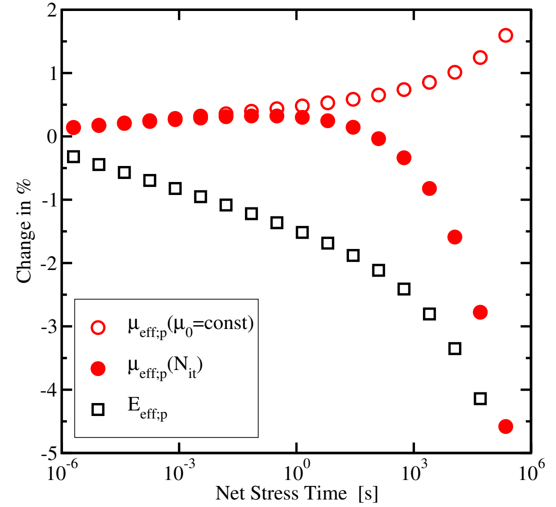


Fig. 8. Time dependence of the effective mobility ($\int \mu_p p \,\mathrm{d}y / \int p \,\mathrm{d}y$) and the effective electric field ($\int E_y p \,\mathrm{d}y / \int p \,\mathrm{d}y$) during the simulated measurement. Here, p is the hole concentration in the channel. When the influence of the interface charges is turned off in the mobility model, the effective mobility *increases* due to the reduction of $|V_{\mathrm{G}} - V_{\mathrm{th}}|$, see [9], while the inclusion of the additional Coulomb scattering at the interface leads to a degradation of about 4% at $t_{\mathrm{s}} = 10^5\,\mathrm{s}$, see [1].

B. OTF Methods

A more involved behavior is observed for ΔV_{th} extracted using the three OTF methods under consideration (cf. Fig. 7). All OTF methods suffer from the delay inherent in the first measurement point [27] which strongly distorts the data and is the equivalent problem of the delay in MSM techniques. We remark, however, that an exact prediction of the influence of the initial delay is difficult and may be exaggerated by assuming the universal relaxation law to be valid also for very short times.

In addition, the three techniques produce markedly different results,

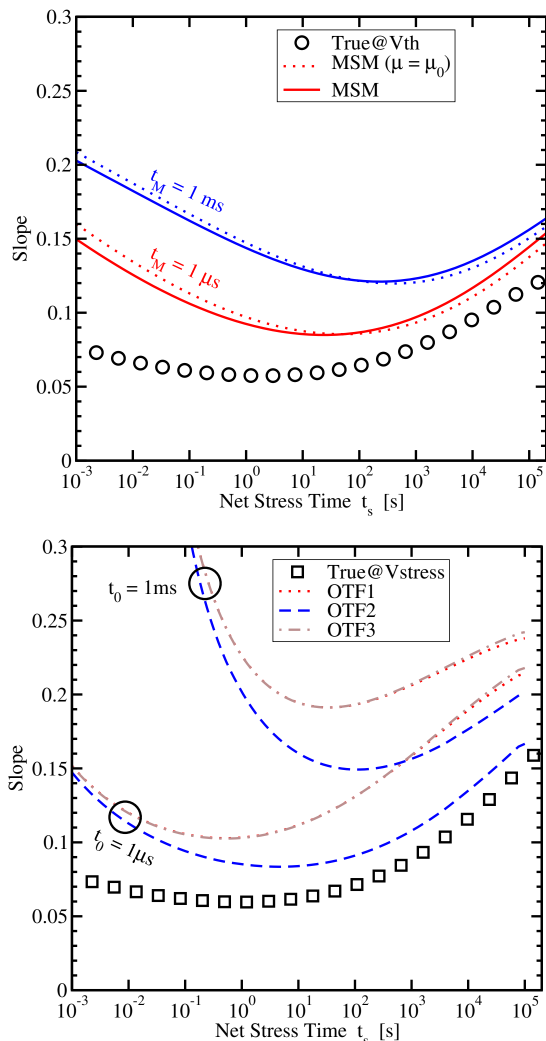


Fig. 9. Influence of the measurement method on the observed slope of an effective power-law time dependence. While the MSM methods (top) depend primarily on the measurement delay t_M, OTF1 and OTF3 are contaminated by t_0 , the mobility variation, and compact modeling errors ($\theta = \mathrm{const}$, etc.). Not even the fastest OTF results are able to reproduce the expected values. In addition, even the good OTF2 results have a larger error in the slopes compared to an (unextrapolated) MSM sequence with $t_\mathrm{M} = t_0$.

with only the OTF2 method [2] being insensitive to mobility changes (cf. Fig. 8). Note also that even extremely fast determination of the initial value $I_{\mathrm{D}0}$ leaves a residual error in the OTF methods due to the use of compact models. This is a rather severe disadvantage considering the widespread use of the OTF1 method in particular [1, 3].

The deficiencies of the OTF methods are also evident in Fig. 9 where the extracted slopes for OTF1 and OTF3 show a considerable error due to the mobility change, in contrast to the MSM method. Finally, we wish to remark that the theoretical accuracy obtainable by the OTF2 method is difficult to realize in practice, because the extracted ΔV_th is extremely sensitive to unavoidable measurement errors in the estimation of g_m [10].

V. Conclusions

We have analyzed the most commonly used NBTI measurement techniques. Our analysis is based on a rigorous numerical solution of the semiconductor device equations, augmented by suitable models for interface and oxide charges. As expected, it is confirmed that MSM methods are distorted by unavoidable delay. Interestingly, MSM methods also contain a small but temperature dependent spurious threshold-voltage shift caused by mobility degradation. OTF methods, on the other hand, suffer from the problem of the initial measurement and can be polluted by rather complex mobility changes. Furthermore, all OTF methods rely on simple compact models for the back-extrapolation of the threshold-voltage shift at stress-level, which results in difficult to quantify inaccuracies.

Overall, it could be confirmed that all measurement techniques used to determine the degradation after bias temperature stress are prone to errors. Nevertheless, in spite of the inherent delay, the smaller systematic errors in the conventional MSM technique allow one to accurately monitor the time evolution of the recovery.

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Questions and Answers

Q: You show that you need unreasonable occupancy cross section to explain recovery in terms of Nit?

A: Yes, the interface states seem to be fast enough and will not have a significant impact on the measured threshold-voltage shift during MSM experiments.

Q: In your model, you assume Nit had no relaxation, and the trapped holes recovered?

A: Yes, but this would not change the conclusions even if Nit was assumed recoverable that OTF is still very sensitive to mobility change effects. Our point was to include one part that relaxed with gate voltage, and another that did not.

Q: You're assuming no interface state recovery in process?

A: For the present analysis we made the assumption that only oxide charges recovery, based on the results published by Huard et. al. However, our charge pumping currents do show recovery, but at a much slower rate. Nevertheless, this is not really important for our conclusions that MSM is not as distorted by mobility variations as on-the-fly measurements.