Negative-bias temperature instability induced electron trapping

J. P. Campbell,1,a) K. P. Cheung,1,b) J. S. Suehle,1 and A. Oates2

1Semiconductor Electronics Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
2TSMC Ltd., Hsin-Chu, Taiwan 300-77, Republic of China

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Despite four decades of research, the physics responsible for the negative-bias temperature instability (NBTI) in p-channel metal-oxide-silicon field-effect transistors is still unresolved. The current NBTI debate focuses on the dominance of either a hole trapping/detrapping mechanism or a hydrogen depassivation mechanism. In this study, we present NBTI-induced changes in the peak transconductance which indicate the presence of a third mechanism involving electron trapping/detrapping. The presence of this electron trapping/detrapping component adds further complexity to the very complicated NBTI phenomenon. © 2008 American Institute of Physics. [DOI: 10.1063/1.2963368]

The negative-bias temperature instability (NBTI) is one of the most important reliability problems in advanced p-channel metal-oxide-silicon field-effect transistors (pMOSFETs).1 It manifests as an increase in absolute threshold voltage (Vth) and degradations in drive current (Id) and channel transconductance (Gm).1 NBTI’s exacerbation in highly scaled pMOSFETs with silicon oxynitride (SiON) gate dielectrics is one of the major reasons for its recent rise in importance.2 Consequently, a considerable research effort has been devoted to determine the mechanism which governs this elusive phenomenon. However, 40 years of research3 has still not led to a definitive understanding of NBTI.

Historically, the physics responsible for NBTI have been debated since the phenomenon was first reported.3 Very early reports indicated that a portion of NBTI-induced degradation is recoverable.4 This partially recoverable degradation is the key feature which distinguishes NBTI models. One faction of researchers believes that NBTI is dominated by the hydrogenic depassivation and repassivation of interface states (reaction-diffusion kinetics)5 while another faction believes that NBTI is dominated by both the depassivation of interface states and a hole trapping/detrapping component. For many years, reaction-diffusion kinetics has been used to explain most NBTI observations. However, the recent development of fast measurement techniques has produced data which are more consistent with the hole trapping/detrapping mechanism.6 An increasing number of recent fast NBTI measurements support a hole trapping/detrapping mechanism.7,8

In this study, we extend our recent speculative reports9,10 to include strong experimental evidence of yet another NBTI mechanism, namely, electron trapping and detrapping. This mechanism contributes to the transient behavior of NBTI, but with a more complex time dependence than hole trapping and detrapping. An increase in electron detrapping after harsher stressing conditions (where the interface state density is presumably higher) indicates that the trapped electrons are at energy levels which require an interface state mediated detrapping process.

Fully processed 2 × 0.06 μm2 and 2 × 0.07 μm2 (physical gate area) pMOSFETs with 1.6 nm SiON gate dielectrics were utilized in this study. Our measurements involve a fast-IdVG technique in which a voltage pulse is applied to the gate electrode while the drain current is monitored using a fast-amplifier circuit.11,12 Both the gate pulse and drain current response are captured and stored on a digital oscilloscope such that the entire IdVG curve is captured at the rising and falling edges of each gate pulse. The gate pulse sequence utilized in this work is schematically illustrated in Fig. 1. The pulse train consists of a trapezoidal “stress” pulse and a triangular postrecovery “sense” pulse separated by a variable recovery time where the gate voltage is held at 0 V. This results in prestress (a), poststress (b), and postrecovery (c) fast-IdVG measurements. Peak-Gm values were extracted for each fast-IdVG measurement with the help of digital filtering. The details and performance of our fast-IdVG measurement methodology are described elsewhere.10 For simplicity, the postrecovery Gm values were taken as the average of the falling and rising measurements of the sense pulse (c). The major contribution of this work stems from an examination of %Gm degradation values between the prestress and postrecovery measurements. A drain voltage of −50 mV is maintained at all times while the source and substrate remain grounded.

Figure 2 illustrates the %Gm degradation as a function of recovery time for devices subject to a NBTI stress of −2.5 V at 125 °C for 10 s. Each data point represents the average of 12 repeated measurements with a fresh device for each recovery time. It is important to note that the stress condition

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a)Electronic mail: jason.campbell@nist.gov.
b)Electronic mail: kin.cheung@nist.gov.
utilized in this study is rather common for NBTI studies of ultrathin gate dielectrics, but represents electric fields which are traditionally categorized as high-field stressing. This high-field stress component is very likely present in most of the reported NBTI literature and will become unavoidable as device scaling continues. It is clear from Fig. 2 that $\%G_M$ is dependent on the recovery time. At very short recovery times (2 µs), $\%G_M$ exhibits degradation. As recovery time increases, $\%G_M$ decreases and transitions to negative values. This corresponds to post-recovery peak-$G_M$ values better than the prestress measurement. At longer recovery times, $\%G_M$ reaches a minimum (maximum improvement) and turns around toward the positive initial degradation values. The observed $G_M$ improvement, albeit brief, is an unexpected result which forces the introduction of an electron trapping/detrapping component to NBTI. While our recent fast-$I_DV_G$ reports detail $V_{th}$ and $G_M$ parametric variations as a function of both stress voltage and stress time, this recovery time study is the first to clearly demonstrate the presence of a NBTI-induced electron trapping/detrapping component.

The observed $G_M$ degradation at short recovery times is consistent with the assumption that NBTI generates (1) traditional interface states which, in pMOS devices, are positively charged in inversion and (2) trapped holes in the bulk of the gate dielectric. Both of these species contribute positive charge which increases the Coulombic scattering and degrades $G_M$. Both hole detrapping and interface state repassivation (as assumed in reaction-diffusion kinetics) can explain the reduction in $\%G_M$ degradation as the recovery time increases. However, neither mechanism is capable of improving $G_M$ to values better than before stress. $G_M$ improvement is only possible by realizing that there must be trapped electrons in the gate dielectric which can effectively counteract the positively charged interface states to reduce Coulombic scattering and improve $G_M$. Observation of $G_M$ improvement due to electron trapping is rare, but not without precedent. For example, Charpenel et al. observed $G_M$ improvement after injecting electrons into the gate dielectric. The complete $\%G_M$ behavior can be explained as follows. Stress traps both holes and electrons in the gate dielectric and generates positively charged (during measurement) interface states. At the conclusion of stress, the combination of trapped holes and interface states overwhelms the trapped electrons, and we observe a net increase in positive charge and Coulombic scattering, which is observed as $G_M$ degradation. It is known that holes detrapp faster than electrons. Thus, as the recovery time increases and the hole concentration decreases, the net positive charge and Coulomb scattering also decrease. This leads to a reduction in the $G_M$ degradation. This process continues until the trapped holes are largely depleted, leaving only the trapped electrons in the bulk. The net positive charge is now at a minimum (and could even be negative). If the net positive charge is less than the amount before stress, $G_M$ improvement will result, as the case in Fig. 2. At longer recovery times, the electrons eventually detrapp, which diminishes the net negative charge in the dielectric and reduces the interface state compensation. Only the positively charged interface states remain, and $G_M$ returns to degradation.

Further evidence supporting our electron trapping hypothesis comes from the observation that $G_M$ improvement is only observable using very fast measurement times. Figure 3 illustrates $\%G_M$ as a function of measurement time (rise or falling time of the gate pulse) for various recovery times. Depending on the recovery time, $\%G_M$ exhibits improvement or degradation. Clearly, this transient $G_M$ behavior is only observable when the measurement time is less than 10 µs. This behavior is also consistent with electron trapping by realizing that the formation of an inversion layer of holes will neutralize any trapped electrons via tunneling. Since the gate dielectric is only 1.6 nm thick, the tunneling front rapidly reaches the trapped electrons. Consequently, only fast measurements (faster than inversion layer formation and tunneling neutralization times) are capable of observing this electron trapping phenomenon. We recently reported this measurement time effect and tentatively attributed the behavior to the presence of trapped electrons. An examination of our somewhat expanded $G_M$ observations as a function of measurement time (Fig. 3) and our systematic examination of recovery time (Fig. 2) very strongly indicate the presence of an electron trapping/detrapping mechanism. This electron trapping/detrapping mechanism is hidden in typical NBTI $V_{th}$ characterizations by the relatively large positive charge accumulation and depletion. The identification of the electron trapping/detrapping component was only possible due to our...
measurement technique, $G_M$ extraction, and careful characterization of the recovery time period.

In an effort to further examine the electron trapping/detrapping phenomenon, the experiment was repeated using a harsher stress condition (−2.7 V at 125 °C for 1000 s). Figure 4 illustrates the $\%G_M$ degradation as a function of recovery time for this harsher stress condition. Since this harsher stress very likely introduces a permanent degradation, no averaging was used for these measurements. It is important to note that the $G_M$ turnaround now occurs at a much shorter recovery time. This suggests that both holes and electrons detrapp much faster. The perceived faster hole detrapping may be due to a much higher trapped hole concentration or may simply be a consequence of faster electron detrapping which obscures the actual hole detrapping. It is even possible that the hole detrapping rate may not have changed. However, the faster electron detrapping is, without question, real. It is difficult to explain why a harsher stress would increase the electron detrapping rate if the electrons detrapp to either the conduction or valence bands. (The harsher stress should have no effect.) This leads to the conclusion that the electron detrapping must be assisted by interface states and that the electrons must detrapp to the substrate, not the gate electrode. Within this framework, a harsher stress would presumably lead to a higher interface state density which allows for a faster electron detrapping rate.

In summary, a rare $G_M$ improvement was observed for a brief duration after NBTI stress. Our results are consistent with an additional NBTI-induced electron trapping/detrapping component occurring in parallel with the well-known hole trapping and interface state generation. Post-stress detrapping of both holes and electrons produces complex transistor parameter shifts. Qualitative analysis of the electron detrapping process suggests that the trapped electrons detrapp to the substrate and require the help of interface states. The identification of this electron trapping/detrapping mechanism further refines the current understanding of NBTI.

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