Electron Trapping: An Unexpected Mechanism of NBTI and its Implications

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INTRODUCTION

NBTI is the most important reliability problem in advanced CMOS technology.[1] Consequently, the recent CMOS reliability literature is dominated by the characterization and modeling of NBTI. All of the existing literature attributes the NBTI-induced ΔV_{TH} and I_D degradation to interface state generation and/or hole trapping.[2] **In this work, we demonstrate that electron trapping has been overlooked in previous studies and will greatly impact the current understanding of the NBTI phenomenon and consequent lifetime predictions.**

KEY RESULT

The key experimental evidence demonstrating electron trapping during NBTI is shown in figure 1 which illustrates the %peak-G_M degradation as a function of recovery time. 1.6nm SiON pMOSFETs were subjected to an NBTI stress of -2.5V/125C/10secs. Figure 2 illustrates our measurement sequence in which an I_dV_g measurement is taken on the rising edge (pre-stress) and falling edge (post-stress) of the gate pulse as well as after a variable recovery period (post-recovery). Each data point represents an average of 12 measurements and a fresh device is used for each recovery time. The pre-stress/post-stress or "zero–recovery" %G_M degradations are shown in figure 1 for reference. Demonstration of electron trapping is found from a comparison of the pre-stress/post-recovery or "recoverable" data which is clearly dependent on the recovery time. Significant G_M degradation is clearly evident at the shortest recovery time (2 µsecs). However, as the recovery time increases, the G_M degradation clearly reduces and crosses over to G_M values **greater than before stress** (negative values on figure 1). At longer recovery times, the G_M values return to the degraded state. This G_M behavior has never been reported since G_M extraction is usually difficult to obtain from fast-I_dV_g measurements. The full G_M curves are shown in figure 3 for the G_M degradation (fig. 3(a)) and G_M improvement (fig. 3(b)) cases.

The observed G_M behavior can be explained by hole as well as electron trapping and detrapping. Although our stress condition is rather common for NBTI studies of ultra thin gate dielectrics, it represents an electric field that is traditionally categorized as high-field stressing. Under high-field stress, it is known [3] that both electron- and hole-trapping occurs. It is also known that both electrons and holes will detrap once the stress is removed, but with very different detrapping rates (with holes detrapping faster).[4] At the conclusion of stress, both trapped holes and trapped electrons are present, along with positively charged interface states (I-V measurement condition) and we observe a maximum G_M degradation. As the recovery time increases, the much higher rate of hole-detrapping leads to a decrease in net trapped charge (bulk plus interface) as well as Coulombic scattering. Thus, the measured G_M degradation is reduced. This continues until the trapped holes in the bulk are largely depleted and electron-detrapping has a stronger impact on the net charge in the bulk. At this point the net charge in the bulk is negative and it is over compensating the positive interface charges added by the stress, leading to G_M improvement. At longer recovery times, electron detrapping continues and the net negative charge in the dielectric diminishes. This leaves only the positive interface state charge and the G_M returns to degradation.

EXPERIMENTAL

Fully processed 2 x 0.07µm^2 and 2 x 0.06µm^2 (physical gate area) SiON pMOSFETs (T_{ox} = 1.6nm) were used in this work. Our fast-I_dV_g measurement (2 digital oscilloscopes, 2 pulse generators, and a fast amplifier circuit)is capable of $\approx$ 2 µsec measurement time. The **unique capability** that enables this work is the ability to perform stress over a time scale from microseconds to essentially infinite time while maintaining the ability of controlling the recovery time to better than a microsecond. Figures 4(a) and 4(b) illustrate the very good agreement between the raw and filtered data from our fast-I_dV_g measurement and the DC measurement using a parametric analyzer. Figure 4(c) illustrates the extracted G_m characteristic from the fast-I_dV_g measurement which also shows very good agreement with the DC-measurement.

It is important to note that the effect of electron trapping can only be seen with a sufficiently fast I_dV_g measurement. Figure 5 illustrates the measured recoverable (-2.5/125C/10sec) %G_M degradation as a function of measurement time (rise/fall time of the gate pulse) for several different recovery times. It is clear that the measurement time must be less than 10usecs to observe the aforementioned G_M trends. It is also clear, that the recovery time greatly alters the result as the 10µsec recovery time exhibits a G_M degradation while the 100msec and 10sec recovery times exhibit a G_M improvement (negative values in figure 5).

RESULTS AND DISCUSSION

One would expect the hole and electron detrapping phenomenon which is affecting the G_M characteristics to also be reflected in the ΔV_{TH} measurement. However, we find that this trend is much harder to observe in the ΔV_{TH} measurements (figure 6) that were extracted from the same I_dV_g measurements used to produce figure 1 (linear extrapolation at max G_M). This is because this stress conditions results in a relatively small ΔV_{TH} which is overwhelmed by the error of the measurement. We have previously reported [5] zero-recovery and recoverable (5 seconds) ΔV_{TH} and %G_M degradations as a function of stress voltage for various stressing times at 125°C (figure 7). It is clear from these measurements that a large initial ΔV_{TH} is only observable at *exceedingly high* stress voltages and long stress times. Similarly, G_M improvement is easier to observe at higher stress voltages (figure 8).

In an effort to correlate V_{TH} behavior with G_M, we repeated our experiment using a harsher stress condition (-2.7V/125C/1000secs). Figures 9 and 10 illustrate the zero-recovery and recoverable ΔV_{TH} and %G_M degradations as a function of recovery time for this harsher stress case. In this case, the ΔV_{TH} trend (figure 9) mimics the G_M trends as expected (fig 10). Note that both hole-detrapping and electron-detrapping rates are higher in this case which results in a G_M turn around at a much earlier recovery time. Electron-detrapping is assisted by interface states via trap-to-trap tunneling. The detrapping rate increase is a result of the much higher interface state density due to the hasher stress. The higher hole-detrapping rate is the normal result of higher stress voltage [6]. The observed earlier G_M turn around time thus further supports our interpretation.

CONCLUSION

We have clearly demonstrated for the first time that the trapping and detrapping of electrons play a major role during common NBTI stressing and recovery conditions. We also showed that both hole-detrapping and electron-detrapping rates are dependent upon the stress condition and both slow down at less severe stress conditions. Furthermore, it is known that hole-detrapping is insensitive to temperature while electron-detrapping is highly sensitive to temperature. At lower temperatures, electron detrapping can be extremely slow. These factors greatly complicate both the characterization and modeling of NBTI. These results indicate that without accounting for the electron trapping and detrapping, the life-time projection of NBTI based on the previously suggested physical models may be unreliable.

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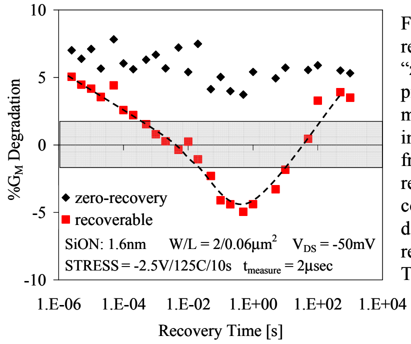

Figure 1: $\%G_M$ degradation as a function of recovery time for pre-stress/post-stress or "zero-recovery" measurements as well as pre-stress/post-recovery or "recoverable" measurements. As the recovery time increases, the recoverable G_M transitions from degradation to improvement and then returns to degradation. This behavior is consistent with both hole and ***electron*** detrapping. The box centered about 0% represents 1 standard deviation error bar. The lines are only a guide for the eye.

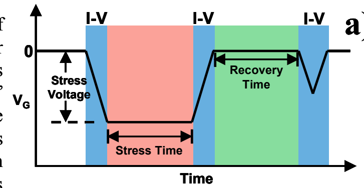

Figure 2: Schematic diagram of the gate voltage pulses during the NBTI stress and measurement sequences. The extracted V_{TH} and G_M values are compared pre-stress/post-stress ("zero-recovery"), and pre-stress/post-recovery ("recoverable").

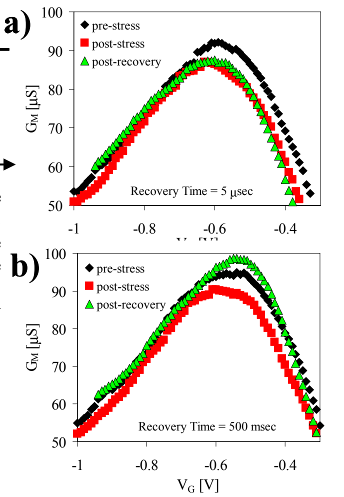

Figure 3: Pre-stress, post-stress, and post-recovery G_M characteristic curves for device subject to -2.5V/125C/10sec. (a) 5μsec recovery time exhibits a post-recovery G_M degradation while (b) 500msec recovery time exhibits a post-recovery G_M improvement.

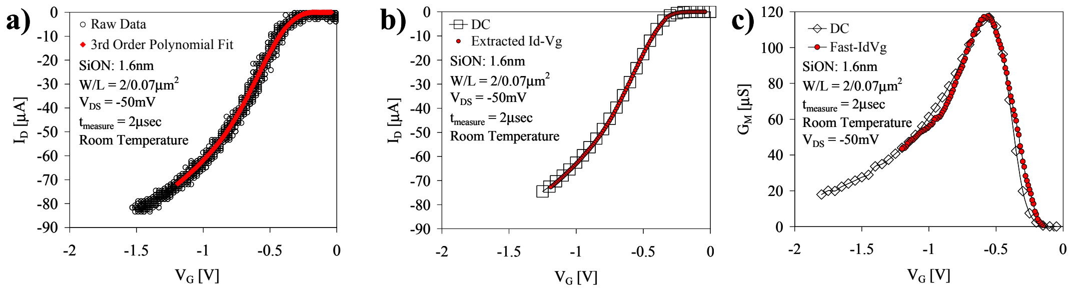

Figure 4: Fast-I_dV_g characteristics obtained using our measurement approach are subject to significant noise. We utilize a "moving" third-order polynomial fitting procedure to extract the I_dV_g characteristic curves from the raw data (a). Our extracted I_dV_g (b) and G_M (c) characteristics agree very well with DC measurements.

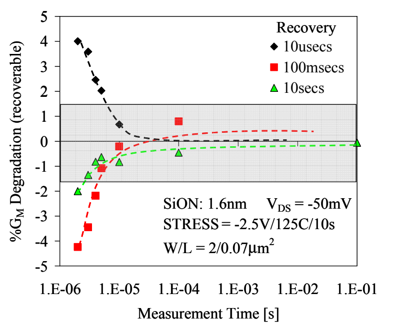

Figure 5: "Recoverable" $\%G_M$ degradation as a function of measurement (rise and fall) time for various recovery times. It is important to note that the G_M degradation/improvement is only observable for measurement times < 10usecs and that the recovery time greatly effects the G_M measurement result. The box centered at 0% represents 1 standard deviation error bar. The lines are only a guide for the eye.

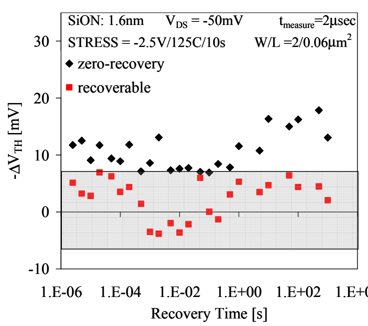

Figure 6: ΔV_{TH} as a function of recovery time for the "zero-recovery" and "recoverable" measurements. The ΔV_{TH} from this stress condition is too small to observe the trend seen in figure 1. The box centered about 0mV represents 1 standard deviation error bar.

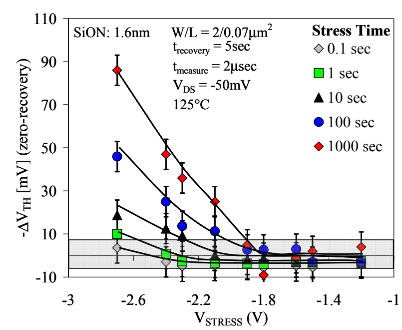

Figure 7: "Zero-recovery ΔV_{TH} as a function of stress voltage for various stress times. It is clear that the fast NBTI degradation only occurs for exceedingly high stress voltages and longer stress times. The box centered about 0mV represents 1 standard deviation error bar. The lines are only a guide for the eye.

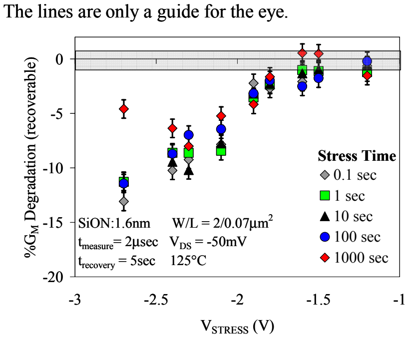

Figure 8: "Recoverable" $\%G_M$ degradation as a function of stress voltage for various stress times. The G_M improvement effect is increases with stress voltage. The box centered about 0% represents 1 standard deviation error bar.

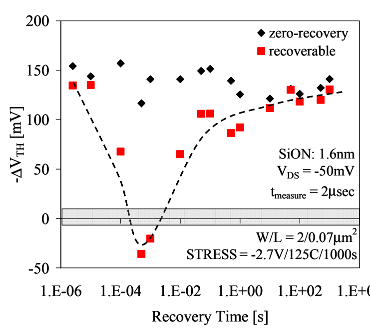

Figure 9: ΔV_{TH} degradation as a function of recovery time for the "zero-recovery" and "recoverable" measurements. At this harsher stress condition (-2.7V/125C/1000sec) the ΔV_{TH} mimics the G_M behavior. The box centered about 0mV represents 1 standard deviation error bar. The lines are only a guide for the eye.

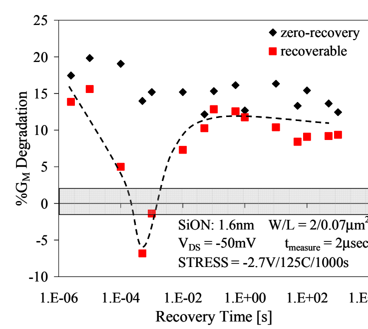

Figure 10: G_M degradation as a function of recovery time for "zero-recovery" and "recoverable" measurements. The GM improvement occurs much faster at this harsher stress condition. The box centered about 0% represents 1 standard deviation error bar. The lines are only a guide for the eye.