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A Common Framework of NBTI Generation and Recovery in Plasma-Nitrided SiON p-MOSFETs

S. Deora, V. D. Maheta, A. E. Islam, M. A. Alam, and S. Mahapatra

Abstract—Generation and recovery of degradation during and after negative bias temperature instability (NBTI) stress are studied in a wide variety of plasma-nitrided (PN) silicon oxynitride (SiON) p-MOSFETs. An ultrafast on-the-fly linear drain current ($I_{DLIN}$) technique, which is capable of measuring the shift in threshold voltage from very short (approximately in microseconds) to long (approximately in hours) stress/recovery time, is used. The mechanics of NBTI generation and recovery are shown to be strongly correlated and can be consistently explained using the framework of an uncorrelated sum of a fast and weakly temperature ($T$)-dependent trapped-hole ($\Delta V_h$) component and a relatively slow and strongly $T$-activated interface trap ($\Delta V_{IT}$) component. The SiON process dependence are attributed to the difference in the relative contributions of $\Delta V_h$ and $\Delta V_{IT}$ to the overall degradation ($\Delta V_T$), as dictated by the nitrogen (N) content and thickness of the gate insulator.

Index Terms—Generation, hole trapping, interface trap generation, negative bias temperature instability (NBTI), p-MOSFET, recovery.

I. INTRODUCTION

Threshold-voltage shift ($\Delta V_T$) during NBTI stress is known for its strong SiON process dependence [1]–[4]. Recently, degradation during NBTI stress on p-MOSFETs having wide range of SiON processes (variation in nitrogen (N) density and thickness) has been studied [4] using an ultrafast on-the-fly (UF-OTF) $I_{DLIN}$ method [5]. Based on these results, SiON process dependence has been attributed to the relative differences in trapped holes ($\Delta V_h$'s) in preexisting bulk insulator traps and generation of interface traps ($\Delta V_{IT}$'s) that contribute to the overall $\Delta V_T$. For the stress phase, the $\Delta V_h$ and $\Delta V_{IT}$ contributions to the overall $\Delta V_T$ have been consistently separated for p-MOSFETs having different plasma-nitrided (PN) SiON processes [6]. It has been shown that $\Delta V_h$ and $\Delta V_{IT}$ generation does not show any correlation as SiON processes and stress conditions are varied. Once $\Delta V_h$ that shows fast saturation and weak temperature ($T$) dependence is taken into account, the remaining degradation can be attributed to $\Delta V_{IT}$ having self-consistent time and $T$ dependence.

It is now well known that defects generated during NBTI stress recover after the stress is removed [7]. However, unlike the stress phase, the SiON process dependence of the recovery phase has not been explored in detail, particularly by using ultrafast techniques that are essential to capture the early-recovery phase (in submilliseconds). The recovery of $\Delta V_h$ and $\Delta V_{IT}$ and the correlation of recovery phase to stress phase for different SiON processes are not yet established. Hence, there is an ongoing debate on the physical mechanism of recovery, particularly its dominance by $\Delta V_h$, $\Delta V_{IT}$, or the correlated combination of both $\Delta V_h$ and $\Delta V_{IT}$ [1], [8]–[14].

In this letter, NBTI degradation and recovery in PN SiON p-MOSFETs are studied using the UF-OTF $I_{DLIN}$ method [5]. A strong process-dependent correlation between stress and recovery is demonstrated. Relative $\Delta V_h$ and $\Delta V_{IT}$ contribution from stress is used to identify/isolate the respective recovery of $\Delta V_h$ and $\Delta V_{IT}$. Similar to the stress phase where the early phase is dominated by hole trapping having negligible $T$ dependence, the early-recovery phase is dominated by hole detrapping having negligible $T$ dependence. Long-term degradation and recovery are dominated by generation and recovery of interface traps and show strong $T$ dependence. Finally, the ($T$) dependence of recovery is correlated to the $T$ dependence of power-law time exponent ($\eta$) obtained during stress using measure–stress–measure (MSM) methods having various measurement delays [8], which has so far not been consistently explained.

II. RESULTS AND DISCUSSION

PN SiON p-MOSFETs ($W/L = 15/0.16$ μm; see [4] for details), having various equivalent oxide thicknesses (EOTs) of 1.4–2.4 nm, and atomic N density of 20%–42% were used. The details of the UF-OTF $I_{DLIN}$ setup have been presented in [5]. During stress, the measured $I_{DLIN}$ transients at $V_G = V_{GSTR}$ are given by $\Delta V_T = -\Delta V_{DLIN}/I_{DLIN} \ast (V_{GSTR} - V_{TO})$, where $V_{GSTR}$ is the stress gate bias, $V_{TO}$ is the prestress $V_T$, $I_{DLIN}$ is the peak $I_{DLIN}$ obtained at a “time-zero” delay of $t_0$ (1 μs, unless mentioned otherwise) after the application of stress, and $\Delta V_{DLIN}$ is the degradation in $I_{DLIN}$ from $I_{DLINO}$. During recovery, transients were extracted at $V_G = V_{REC}$, and a similar expression was used (with $V_{GSTR}$ being replaced by $V_{REC}$), where $V_{REC}$ is the recovery bias applied after the removal of stress, and $I_{DLIN}$ is the first measurement point in time $t_0$ (again, 1 μs) after $V_G$ goes from $V_{GSTR}$ to $V_{REC}$.

Note that OTF $\Delta V_T$ is proportional to but different from conventional $\Delta V_T$ (obtained from transfer $I$–$V$ sweeps), as mobility degradation is not taken into account [15].

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Fig. 1. (LHS) Time evolution of the measured $\Delta V$ at different $t$'s but constant $E_{OX}$ during stress, and (RHS) time evolution of the fractional degradation remaining during recovery for different stress times at constant $T$ and poststress $E_{OX}$ for a 1.46-nm EOT and 42% N device.

Fig. 2. Hole-trap fraction as a function of (LHS) stress time at constant $T$ and (RHS) stress $T$ at constant stress time for devices having different EOTs and N%’s. This time is defined as hole-detrapping time during the early-recovery phase (see the text).

If the submillisecond part of the stress phase is dominated by hole trapping (having negligible $T$ activation) that is subsequently overtaken by relatively slow (but nonsaturating, having strong $T$ activation) generation of interface traps, one would expect the following features during the recovery phase: 1) the early submillisecond part of recovery will also be dictated by negligibly $T$-dependent hole detrapping; 2) the hole-detrapping time would be independent of stress time or stress $T$ (provided that generation of oxide traps is negligible, which is true as long-time exponent $n$ remains independent of stress $V_G$ [18]); and 3) the $T$- and stress-time-dependent components would diverge once the component due to holes has detrapped.

To verify the aforementioned hypothesis that early recovery is dominated by fast $\Delta V_h$ detrapping, and the onset of $\Delta V_{IT}$ recovery is delayed, Fig. 3 shows the extracted recovery time from fractional $\Delta V_h$ transients (see Fig. 1, RHS) corresponding to fractional $\Delta V_h$ (see Fig. 2) as a function of stress time and stress $T$ under constant stress field ($E_{OX,S}$) and recovery field ($E_{OX,R}$) for a wide variety of SiON processes. This time, defined as hole-detrapping time ($t_h$), increases with the increase in N% (changes according to the applied $E_{OX,S}$ and $E_{OX,R}$) for different SiON films but, most importantly, remains invariant to stress time and stress/recovery $T$, exactly as expected. This can only be explained if the early-recovery phase is dominated by $\Delta V_h$ recovery. As a result, although $\Delta V_h$ fraction is different for different stress times and $T$'s (see Fig. 2), $t_h$ corresponding to $\Delta V_h$ recovery remains identical as the magnitude of $\Delta V_h$ is identical for various stress times (due to fast $\Delta V_h$ saturation) and stress $T$'s (due to negligible $T$ activation of $\Delta V_h$ [6]). A correlated recovery of $\Delta V_h$ and $\Delta V_{IT}$ at the early-recovery phase would result in different $t_h$’s as a function of stress duration and stress/recovery $T$, contrary to the observed results.

To further verify the $\Delta V_h$ dominance of early recovery, Fig. 4 shows (LHS) the time evolution of $\Delta V_T$ recovery under different stress $T$'s for SiON devices having different N%’s. Note that recovery is $T$ independent at early-recovery time, presumably due to weak $T$ activation of hole detrapping, and the time up to which recovery remains $T$ independent is $\sim 0.1 \text{ ms}$.
III. CONCLUSION

To summarize, the use of the UF-OTF technique has helped capture the short- and long-time generation and recovery phases of NBTI. Trapped holes ($\Delta V_h$'s) and generated interface traps ($\Delta V_{IT}$'s) that contribute to the overall degradation ($\Delta V_T$) are shown to vary with SiON processes (N% and EOT) and stress conditions, although $\Delta V_h$ and $\Delta V_{IT}$ always remain uncorrelated to each other. However, NBTI recovery is shown to be strongly correlated to generation. The early (submillisecond) phase of both generation and recovery is shown to be governed by weakly T-dependent hole trapping and detrapping processes. The longer time phase is governed by generation and passivation of interface traps having strong T dependence. The mutually uncorrelated $\Delta V_h$ and $\Delta V_{IT}$ generation and recovery highlight the differences in stress and recovery behaviors of the overall $\Delta V_T$ for differently processed SiON devices.

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