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A common framework of NBTI generation and recovery in plasma-nitrided SiON p-MOSFETs

Shwetad Deora

V. D. Maheta

A. E. Islam

M. A. Alam

Souvik Mahapatra

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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 (ΔV_h) component and a relatively slow and strongly T-activated interface trap (ΔV_{IT}) component. The SiON process dependences are attributed to the difference in the relative contributions of ΔV_h and ΔV_{IT} to the overall degradation (ΔV_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 (ΔV_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 (ΔV_h's) in preexisting bulk insulator traps and generation of interface traps (ΔV_{IT}'s) that contribute to the overall ΔV_T. For the *stress phase*, the ΔV_h and ΔV_{IT} contributions to the overall ΔV_T have been consistently separated for p-MOSFETs having different plasma-nitrided (PN) SiON processes [6]. It has been shown that ΔV_h and ΔV_{IT} generation does not show any correlation as SiON processes and stress conditions are varied. Once ΔV_h that shows fast saturation and weak temperature (T) dependence is taken into account, the remaining degradation can be attributed to ΔV_{IT} having self-consistent time and T dependence.

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S. Deora, V. D. Maheta, and S. Mahapatra are with the Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai 400076, India (e-mail: shwetad@ee.iitb.ac.in; vrajesh@ee.iitb.ac.in; souvik@ee.iitb.ac.in).

A. E. Islam and M. A. Alam are with the School of Electrical Engineering and Computer Science, Purdue University, West Lafayette, IN 47907-2035 USA (e-mail: aeislam@purdue.edu; alam@purdue.edu).

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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 ΔV_h and ΔV_{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 ΔV_h, ΔV_{IT}, or the correlated combination of both ΔV_h and ΔV_{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 ΔV_h and ΔV_{IT} contribution from stress is used to identify/isolate the respective recovery of ΔV_h and ΔV_{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 (in)dependence of recovery is correlated to the T (in)dependence of power-law time exponent (n) 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 $V_G = V_{\mathrm{GSTR}}$ are given by $\Delta V_T = -\Delta I_{\mathrm{DLIN}}/I_{\mathrm{DLIN0}} * (V_{\mathrm{GSTR}} - V_{\mathrm{T0}})$, where V_{GSTR} is the stress gate bias, V_{T0} is the prestress V_T, I_{DLIN0} 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 ΔI_{DLIN} is the degradation in I_{DLIN} from I_{DLIN0}. During recovery, transients were extracted at $V_G = V_{\mathrm{REC}}$, 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_{DLIN0} 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 ΔV_T is proportional to but different from conventional ΔV_T (obtained from transfer I–V sweeps), as mobility degradation is not taken into account [15].

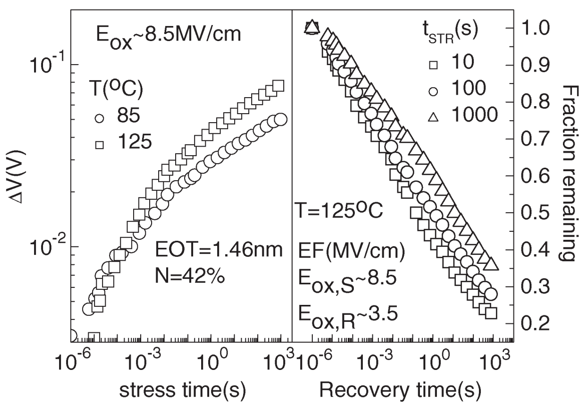

Fig. 1. (LHS) Time evolution of the measured ΔV at different T's but constant E_{OX} during stress, and (RHS) time evolution of the fractional degradation remaining during recovery for different stress times at constant T and poststress E_{OX} for a 1.46-nm EOT and 42% N device.

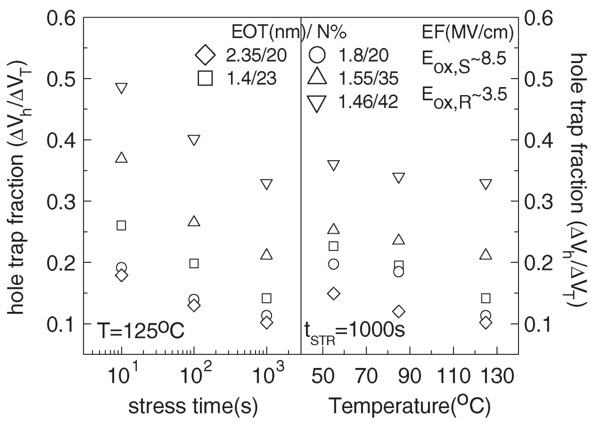

Fig. 2. Hole-trap fraction as a function of (LHS) stress time at constant T and (RHS) stress T at constant stress time for devices having different EOTs and N%'s.

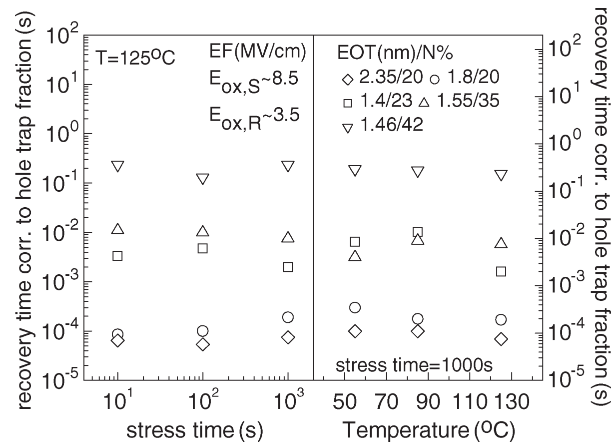

Fig. 3. Time during recovery corresponding to hole-trap fraction as a function of (LHS) stress time at constant T and (RHS) stress T at constant stress time for devices having different EOTs and N%'s. This time is defined as hole-detrapping time during the early-recovery phase (see the text).

Fig. 1 shows [left-hand side (LHS)] the time evolution of ΔV_T during stress at different stress T's under identical oxide electric field (E_{OX}) and [right-hand side (RHS)] the fractional ΔV_T remaining (i.e., yet to recover) during recovery (following different stress times), at identical stress/recovery E_{OX} and T, for $N = 42\%$ and an EOT $= 1.46$-nm SiON device. Very large T-independent short-time (submillisecond) degradation has been identified as due to ΔV_h, while long-time degradation has been correlated to ΔV_{IT} [6]. Assuming fast saturation $(t < 1$ s) of ΔV_h, a constant ΔV_h has been subtracted from long time $(t > 10$ s$)\Delta V_T$ to obtain ΔV_{IT} that shows $n = 0.16$ (see [6] for details), which remains consistent with very long-time stress data [16], [17]. Such an isolation method has been shown to yield consistent E_{OX} and T dependence of ΔV_h and ΔV_{IT} over a wide range of N%'s and EOTs of the SiON gate insulator. Fig. 2 shows the extracted ΔV_h fraction $(\Delta V_h/\Delta V_T)$ as a function of stress time and stress/recovery T for different SiON processes. Note that ΔV_h fraction increases with N%, reduces with stress time (as ΔV_h saturates fast while ΔV_{IT} and ΔV_T keep growing), and reduces with stress/recovery T (as ΔV_{IT} has higher T activation than ΔV_h). It is evident from Fig. 2 that the relative magnitudes of ΔV_h and ΔV_{IT} are different (therefore, ΔV_h and ΔV_{IT} are not correlated) as stress parameters, as well as the SiON process (N% and EOT), are varied.

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 ΔV_h detrapping, and the onset of ΔV_{IT} recovery is delayed, Fig. 3 shows the extracted recovery time from fractional ΔV_T transients (see Fig. 1, RHS) corresponding to fractional ΔV_h (see Fig. 2) as a function of stress time and stress T under constant stress field $(E_{\mathrm{OX},S})$ and recovery field $(E_{\mathrm{OX},R})$ 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 $E_{\mathrm{OX},S}$ and $E_{\mathrm{OX},R}$) 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 ΔV_h recovery. As a result, although ΔV_h fraction is different for different stress times and T's (see Fig. 2), t_h corresponding to ΔV_h recovery remains identical as the magnitude of ΔV_h is identical for various stress times (due to fast ΔV_h saturation) and stress T's (due to negligible T activation of ΔV_h [6]). A correlated recovery of ΔV_h and ΔV_{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 ΔV_h dominance of early recovery, Fig. 4 shows (LHS) the time evolution of ΔV_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 ~0.1 ms

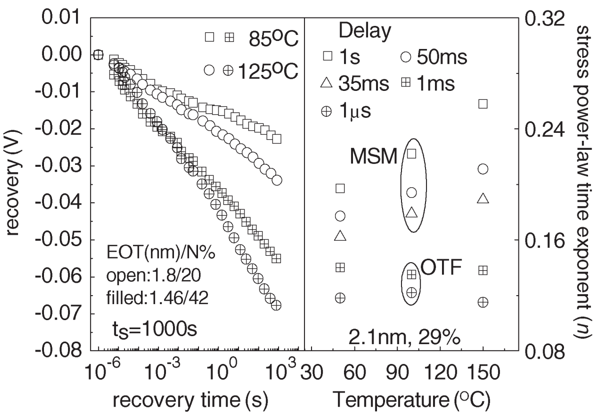

Fig. 4. (LHS) Time evolution of recovery at different T's for devices having different EOTs and N%'s at $E_{\mathrm{OX},S} \sim 8.5$ MV/cm and $E_{\mathrm{OX},R} \sim 3.5$ MV/cm. (RHS) Power-law time exponent (10–1000 s) as a function of stress T obtained from MSM, OTF, and UF-OTF measurement techniques under different delays at constant $E_{\mathrm{OX}} \sim 8.5$ MV/cm during stress.

for $\mathrm{N} = 20\%$ and $\sim$100 ms for $\mathrm{N} = 42\%$, consistent with the t_h values obtained for these devices (see Fig. 3). Figs. 1–3 suggest that NBTI generation and recovery for various SiON processes are strongly correlated, and the process dependence (increase in N%) of generation and recovery can be explained by a fast weak T-dependent ΔV_h component and a relatively gradual stronger T-dependent ΔV_{IT} component.

As a further consequence of weak T-activated short-time and strong T-activated long-time recovery, Fig. 4 shows (RHS) the measured power-law time exponent (n) during long-time stress as a function of stress T, which is obtained by the conventional MSM method at various delays [8], as well as OTF $(t_0 = 1\ \mathrm{ms})$ [7] and UF-OTF $(t_0 = 1\ \mu\mathrm{s})$ [5] methods. It is now well known that recovery during measurement delay causes an increase in n [1], [7], [8]. As longer time recovery shows strong T dependence due to the ΔV_{IT}-dominated process, a larger delay time in MSM results in strong T dependence of n [8]. Reduction in delay time implies no ΔV_{IT} recovery and T-independent recovery due to the ΔV_h-dominated process. Therefore, n remains independent of stress T when measured using OTF or UF-OTF processes having millisecond or lower delays.

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 (ΔV_h's) and generated interface traps (ΔV_{IT}'s) that contribute to the overall degradation (ΔV_T) are shown to vary with SiON processes (N% and EOT) and stress conditions, although ΔV_h and ΔV_{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 ΔV_h and ΔV_{IT} generation and recovery highlight the differences in stress and recovery behaviors of the overall ΔV_T for differently processed SiON devices.

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