Hole energy dependent interface trap generation in MOSFET Si/SiO2 interface

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Hole Energy Dependent Interface Trap Generation in MOSFET Si/SiO$_2$ Interface

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***Abstract*—The nature and composition of generated interface-trap (ΔN_{IT}) in p-MOSFETs is studied as a function of hole energy. By observing the time dependence of generation during stress and the amount of recovery after stress, it is shown that ΔN_{IT} is due to both broken ≡Si–H and ≡Si–O– bonds, their ratio governed by hole energy. In the absence of hot holes ΔN_{IT} is primarily composed of broken ≡Si–H, which show a lower power-law time exponent and a fraction of which anneal after stress. *Additional* ΔN_{IT} is created in the presence of hot holes, which is due to broken ≡Si–O– bonds. These traps show a much larger power-law time exponent, and they do not anneal after stress. These observations have important implications for lifetime prediction under negative bias temperature instability, Fowler–Nordheim, and hot carrier injection stress conditions.**

***Index Terms*—Anode hole-injection (AHI) model, charge pumping, Fowler–Nordheim (FN), H release model, interface and bulk traps, MOSFET, negative bias temperature instability (NBTI), reaction-diffusion (R-D) model, stress-induced leakage current (SILC).**

I. Introduction

INTERFACE-TRAP generation (ΔN_{IT}) is an important issue in MOSFETs subjected to negative bias temperature instability (NBTI), hot carrier injection (HCI) and Fowler–Nordheim (FN) stress [1]–[3]. N_{IT} is due to trivalent silicon atoms at Si/SiO$_2$ interface (Si$_3$≡Si–), which show up as P_b centers in ESR studies [4]. ΔN_{IT} during stress is generally believed solely due to rupture of ≡Si–H bonds at the Si/SiO$_2$ interface [5]. The released H species move away and leave behind ≡Si–(N_{IT}), which can be monitored by charge pumping (CP) [6]. The nature (H$_2$, H$^\circ$ or H$^+$) and rate of diffusion of released H species away from the Si/SiO$_2$ interface determines the time evolution of ΔN_{IT}, as explained by the basic [5] and modified [7]–[9] reaction-diffusion (R-D) approaches. While NBTI stress (negligible hot holes) produce only ΔN_{IT} [10], others such as HCI and FN stress (hot holes present) also produce bulk traps (ΔN_{OT}) [11], [12]. ΔN_{OT} is believed to be due to broken ≡Si–O– bonds at oxide bulk and show up as stress-induced leakage current (SILC) [13]–[15].

In this letter, we demonstrate that this simple view of the role of hole energy in producing ΔN_{IT} and ΔN_{OT} is incomplete, and depending on hole energy, ΔN_{IT} may consist of both broken ≡Si–H and ≡Si–O– bonds. Understanding the composition of interface traps has implications for reliability theory and lifetime projection. Specifically, ΔN_{IT} created by low energy holes (e.g., NBTI) has a lower power-law time exponent (n) than that observed for ΔN_{IT} or ΔN_{OT} during HCI [2] or FN stress [10], [12] when hot holes are present. Lower n of ΔN_{IT} for NBTI is explained by the release of either or both neutral H$^\circ$ and H$_2$ [7]. Higher n of ΔN_{IT} for HCI and FN stress can be explained by either (a) release of H$^+$ [7] or (b) broken ≡Si–O– bonds [13] (together with broken ≡Si–H bonds) at the Si/SiO$_2$ interface. Since this scenarios lead to substantially different lifetime projections, it is important to understand and quantify the nature and composition of N_{IT} buildup due to broken ≡Si–H and ≡Si–O– bonds, and check for the release of H$^+$, if any. We know of no effort so far, that has successfully differentiated between these two types of interface trap generation processes.

This letter attempts to isolate and quantify N_{IT} generation due to broken ≡Si–H and ≡Si–O– bonds based on the simple observation that once the stress is removed, ΔN_{IT} associated with ≡Si–H bonds recovers fast [8], [16], while ΔN_{IT} associated ≡Si–O– bonds does not recover. Therefore, various combination of ≡Si–H and ≡Si–O– related defects are created by varying hole energy and their relaxation dynamics are studied. Specifically, this is done by stressing p-MOSFETs at different gate (V_G) and substrate (V_B) voltages and monitoring N_{IT} buildup and recovery for successive stress and post-stress periods. It is shown that when stressed at low $V_G(V_B = 0)$ such that hot hole (HH) generation is negligible, ΔN_{IT} is due to broken ≡Si–H bonds, a fraction of which recovers after stress is removed. When HH generation is increased (by increasing V_B) for any stress V_G [10], [17], enhanced ΔN_{IT} is observed. HH induced *additional* ΔN_{IT} does not recover and shows a unique power law in time ($n \sim 0.5$) that matches well with that of SILC. It is concluded that the *additional* ΔN_{IT} caused by $V_B > 0$ stress is due to HH induced broken ≡Si–O bonds at the Si/SiO$_2$ interface. Our results have important implications for selection of NBTI, FN and HCI stress voltages, projection of device lifetime under variety of operating conditions, and modeling of interface traps by R-D model.

II. Results and Discussion

Experiments were performed on p-channel non-nitrided gate oxide MOSFETs having oxide thickness (T_{PHY}) of 22, 24, and 26 Å. The devices were stressed at different V_G and V_B to vary the oxide and substrate fields respectively, and were followed by a post-stress period. The stress and post-stress was periodically stopped to measure charge pumping current (fixed pulse amplitude, $f = 800$ kHz) for N_{IT} extraction. Note, traps at and

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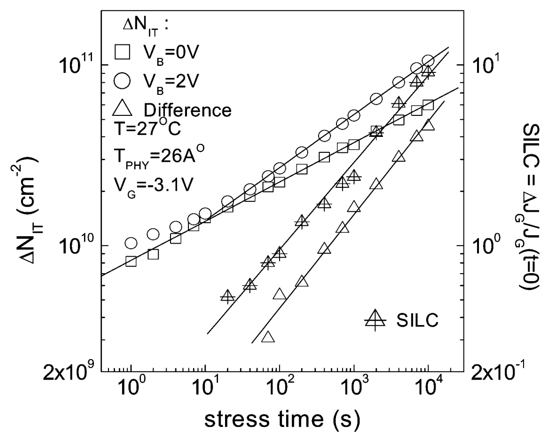

Fig. 1. Time evolution of interface trap density for $V_B = 0$ and 2 V stress. Stressing was done on 26 Å p-MOSFETs at $T = 27\ ^\circ\mathrm{C}$ in inversion. Time evolution of $V_B = 2$ V stress induced enhanced interface trap density and SILC are also shown. SILC was measured at $V_G = -2.5$ V.

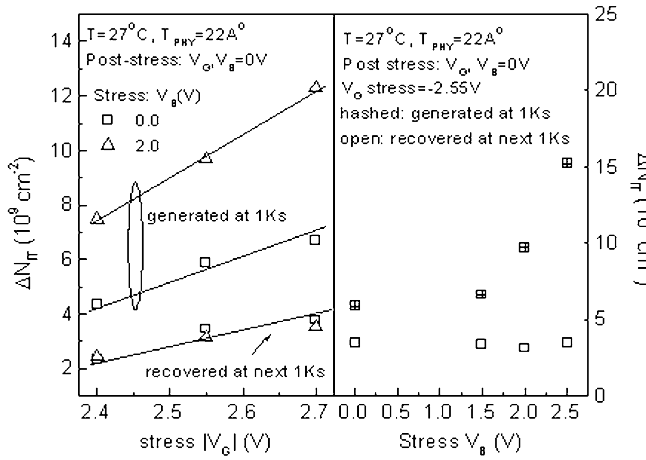

Fig. 2. Interface trap generation at 1000s stress and amount recovered after a subsequent 1000 s post-stress phase. (LHS) For $V_B = 0$ V and $V_B = 2$ V stress at different stress V_G. (RHS) For different stress V_B at a fixed stress V_G. Stressing was done on 22 Å p-MOSFETs at $T = 27\ ^\circ\mathrm{C}$ in inversion. Post-stress $V_G, V_B = 0$ V.

very near the Si/SiO$_2$ interface can respond to charge pumping measurements. Since relaxation during measurement is a concern [18], the delay between stop of stress and start of next stress was 500 ms. High V_G SILC was measured on *separate*, identically stressed devices when required to monitor N_{OT}. Multiple V_G sweeps were performed with delays in-between to nullify any charge trapping induced transient effects [19].

Fig. 1 shows the time evolution of ΔN_{IT} for stress under different V_B but identical V_G. ΔN_{IT} shows a power law in time, with $n \sim 0.2$ for stress at $V_B = 0$. ΔN_{IT} increases with hole energy as stress V_B is increased, and the power law signature is maintained although with a higher value of time exponent $(n \sim 0.3)$. Note, the time beyond which the $V_B > 0$ V induced ΔN_{IT} enhancement shows up reduces as V_B is increased. Time evolution of $V_B > 0$ stress induced *additional* $\Delta N_{\mathrm{IT}}\{\Delta^2 N_{\mathrm{IT}} = \Delta N_{\mathrm{IT}}(V_B > 0) - \Delta N_{\mathrm{IT}}(V_B = 0)\}$ together with measured high-V_G SILC are also shown in Fig. 1. Both *additional* ΔN_{IT} and SILC were observed for $V_B > 0$ stress only when HH generation is significant, show good correlation with quantum yield [10] of HH generation as V_B is increased (not shown), and show a time power law with $n \sim 0.5$. The reason behind higher n for ΔN_{IT} under the presence of HH is explained below.

Note, ΔN_{IT} under normal NBTI $(V_B = 0)$ is due to the rupture of ≡Si–H bonds, and would show a time exponent $n \sim 0.165$ if the diffusing species is H$_2$, and $n \sim 0.25$ if it is H ° [7]. Any intermediate value $(n \sim 0.2)$ can be explained by any of the following: 1) a mix of H$_2$ and H ° species, 2) H ° species plus dispersive transport, and 3) H$_2$ species plus recovery due to measurement delay [7]. Independent measurements of the activation energy of diffusion also points to H$_2$ species [10], [17]. The $n \sim 0.3$ time exponent of enhanced ΔN_{IT} for $V_B > 0$ stress is due to the sum of two components: *normal* ΔN_{IT} with $n \sim 0.2$ plus the *additional* ΔN_{IT} with $n \sim 0.5$ (Fig. 1). Note that depending on stress V_G and $V_B, \Delta N_{\mathrm{IT}}$ for $V_B > 0$ stress shows a wide range of n (not plotted here for brevity) depending on the relative magnitude of *normal* and *additional* components. However, $\Delta^2 N_{\mathrm{IT}}$ always shows a time exponent of $n \sim 0.5$.

The $n \sim 0.5$ time exponent of $\Delta^2 N_{\mathrm{IT}}$ can be due to (a) broken ≡Si–H bonds followed by release of ionic H$^+$ [7], (b) broken ≡Si–O– bonds [13], [20] or (c) both. Note, SILC is always observed together with *additional* ΔN_{IT} in the presence of HH, which clearly identifies that ≡Si–O– bonds are broken [20]. Therefore, at least some of *additional* ΔN_{IT} is due to broken ≡Si–O– bonds at Si/SiO$_2$ interface. It remains to be seen if additional ≡Si–H bonds are also broken with subsequent release of H$^+$, and whether H$^+$ plays some role in breaking ≡Si–O– bonds [21]. To analyze any possible release of H$^+$, the generation and recovery of ΔN_{IT} is monitored for successive stress (with and without V_B) and relax phase. Note, R-D model predicts that once the stress is removed, some of the released H species come back to the interface and rapidly re-passivate ≡Si– to form ≡Si–H, thereby reducing ΔN_{IT} [7], [8]. However, *no known mechanism* exists for the passivation of broken ≡Si–O– bonds.

Fig. 2 shows ΔN_{IT} generation and recovery as a function of stress V_G (LHS) and stress V_B (RHS). As shown in Fig. 2 (LHS), ΔN_{IT} generation and recovery increases with increase in stress V_G (for all stress V_B). However, *additional* ΔN_{IT} generated for $V_B > 0$ V stress (for all stress V_G) does not recover. This becomes clearer from Fig. 2 (RHS), which shows ΔN_{IT} generation increases with stress V_B, but ΔN_{IT} recovery is always identical for all stress V_B (similar to $V_B = 0$ case). Fig. 3 shows ΔN_{IT} generation and recovery as a function of post stress V_G. ΔN_{IT} recovery is always identical for both $V_B = 0$ and $V_B > 0$ stress and is *weakly* dependent on the sign and magnitude of post stress V_G.

Figs. 2 and 3 prove that *additional* ΔN_{IT} generated in the presence of HH does not recover. Therefore, enhanced ΔN_{IT} in the presence of HH for $V_B > 0$ stress is entirely due to additional contribution from broken ≡Si–O– bonds at the Si/SiO$_2$ interface. If H$^+$ions were generated from broken ≡Si–H bonds, a fraction of them should have diffused back to the Si/SiO$_2$ interface and passivate at least a fraction of the additional ≡Si–. Furthermore, the insensitivity of ΔN_{IT} recovery to post stress

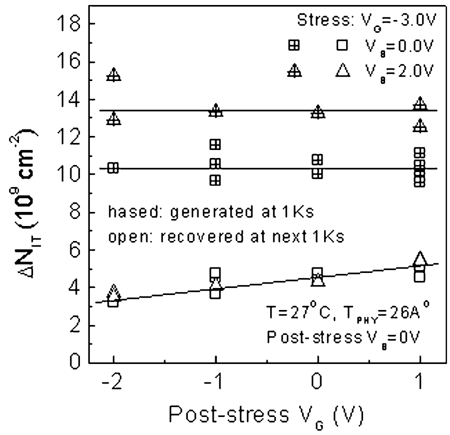

Fig. 3. Interface trap generation for $V_B = 0$ V and $V_B = 2$ V stress and its recovery during a subsequent post-stress phase for different post-stress V_G. Stressing was done on 26 Å p-MOSFETs at $T = 27\,^\circ$C in inversion. Post-stress $V_B = 0$ V for all measurements. Lines are guide to the eye.

V_G (Fig. 3) can only be explained if the returning H species is neutral. This rules out the presence (generation) of H^+ during both $V_B = 0$ and $V_B > 0$ stress.

III. Conclusion

To summarize, the nature of interface trap generation in p-MOSFET is studied by varying the energy of hot holes during NBTI and FN stress. In the absence of hot holes (HH), inversion layer (cold) holes induce ΔN_{IT} by breaking ≡Si–H bonds. Released H species move away as neutral H ° or H_2, yield a time power-law with $n \sim 0.2$, and come back after stress and anneal a fraction of ΔN_{IT} by passivating ≡Si–H bonds. HH generation and subsequent injection into oxide break ≡Si–O– bonds, which appears as *additional* ΔN_{IT} and ΔN_{OT}, show a power-law with $n \sim 0.5$ and does not recover after stress. Overall ΔN_{IT} becomes a sum of normal and *additional* ΔN_{IT} components and shows a power-law with $0.2 < n < 0.5$. Finally, the lack of evidence of H^+ release with HH injection would imply that such a process is an unlikely precursor to generating bulk traps that could lead to time-dependent dielectric breakdown, which has important implications for theories of gate dielectric breakdown.

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