

# Hole Energy Dependent Interface Trap Generation in MOSFET Si/SiO<sub>2</sub> Interface

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**Abstract**—The nature and composition of generated interface-trap ( $\Delta N_{IT}$ ) 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  $\Delta N_{IT}$  is due to both broken  $\equiv\text{Si-H}$  and  $\equiv\text{Si-O-}$  bonds, their ratio governed by hole energy. In the absence of hot holes  $\Delta N_{IT}$  is primarily composed of broken  $\equiv\text{Si-H}$ , which show a lower power-law time exponent and a fraction of which anneal after stress. *Additional*  $\Delta N_{IT}$  is created in the presence of hot holes, which is due to broken  $\equiv\text{Si-O-}$  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 ( $\Delta N_{IT}$ ) 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<sub>2</sub> interface ( $\text{Si}_3\equiv\text{Si-}$ ), which show up as  $P_b$  centers in ESR studies [4].  $\Delta N_{IT}$  during stress is generally believed solely due to rupture of  $\equiv\text{Si-H}$  bonds at the Si/SiO<sub>2</sub> interface [5]. The released H species move away and leave behind  $\equiv\text{Si-}(N_{IT})$ , which can be monitored by charge pumping (CP) [6]. The nature ( $\text{H}_2$ ,  $\text{H}^\circ$  or  $\text{H}^+$ ) and rate of diffusion of released H species away from the Si/SiO<sub>2</sub> interface determines the time evolution of  $\Delta N_{IT}$ , as explained by the basic [5] and modified [7]–[9] reaction-diffusion (R-D) approaches. While NBTI stress (negligible hot holes) produce only  $\Delta N_{IT}$  [10], others such as HCI and FN stress (hot holes present) also produce bulk traps ( $\Delta N_{OT}$ ) [11], [12].  $\Delta N_{OT}$  is believed to be due to broken  $\equiv\text{Si-O-}$  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  $\Delta N_{IT}$  and  $\Delta N_{OT}$  is incomplete, and depending on hole energy,  $\Delta N_{IT}$  may consist of both

broken  $\equiv\text{Si-H}$  and  $\equiv\text{Si-O-}$  bonds. Understanding the composition of interface traps has implications for reliability theory and lifetime projection. Specifically,  $\Delta N_{IT}$  created by low energy holes (e.g., NBTI) has a lower power-law time exponent ( $n$ ) than that observed for  $\Delta N_{IT}$  or  $\Delta N_{OT}$  during HCI [2] or FN stress [10], [12] when hot holes are present. Lower  $n$  of  $\Delta N_{IT}$  for NBTI is explained by the release of either or both neutral  $\text{H}^\circ$  and  $\text{H}_2$  [7]. Higher  $n$  of  $\Delta N_{IT}$  for HCI and FN stress can be explained by either (a) release of  $\text{H}^+$  [7] or (b) broken  $\equiv\text{Si-O-}$  bonds [13] (together with broken  $\equiv\text{Si-H}$  bonds) at the Si/SiO<sub>2</sub> 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  $\equiv\text{Si-H}$  and  $\equiv\text{Si-O-}$  bonds, and check for the release of  $\text{H}^+$ , 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  $\equiv\text{Si-H}$  and  $\equiv\text{Si-O-}$  bonds based on the simple observation that once the stress is removed,  $\Delta N_{IT}$  associated with  $\equiv\text{Si-H}$  bonds recovers fast [8], [16], while  $\Delta N_{IT}$  associated  $\equiv\text{Si-O-}$  bonds does not recover. Therefore, various combination of  $\equiv\text{Si-H}$  and  $\equiv\text{Si-O-}$  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,  $\Delta N_{IT}$  is due to broken  $\equiv\text{Si-H}$  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  $\Delta N_{IT}$  is observed. HH induced *additional*  $\Delta N_{IT}$  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*  $\Delta N_{IT}$  caused by  $V_B > 0$  stress is due to HH induced broken  $\equiv\text{Si-O}$  bonds at the Si/SiO<sub>2</sub> 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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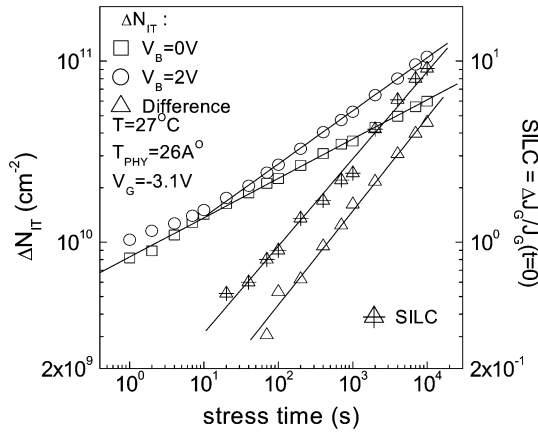


Fig. 1. Time evolution of interface trap density for  $V_B = 0$  and 2 V stress. Stressing was done on 26 Å p-MOSFETs at  $T = 27^\circ\text{C}$  in inversion. Time evolution of  $V_B = 2$  V stress induced enhanced interface trap density and SILC are also shown. SILC was measured at  $V_G = -2.5$  V.

very near the Si/SiO<sub>2</sub> 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  $\Delta N_{IT}$  for stress under different  $V_B$  but identical  $V_G$ .  $\Delta N_{IT}$  shows a power law in time, with  $n \sim 0.2$  for stress at  $V_B = 0$ .  $\Delta N_{IT}$  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  $\Delta N_{IT}$  enhancement shows up reduces as  $V_B$  is increased. Time evolution of  $V_B > 0$  stress induced *additional*  $\Delta N_{IT}$  ( $\Delta^2 N_{IT} = \Delta N_{IT}(V_B > 0) - \Delta N_{IT}(V_B = 0)$ ) together with measured high- $V_G$  SILC are also shown in Fig. 1. Both *additional*  $\Delta N_{IT}$  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  $\Delta N_{IT}$  under the presence of HH is explained below.

Note,  $\Delta N_{IT}$  under normal NBTI ( $V_B = 0$ ) is due to the rupture of  $\equiv\text{Si-H}$  bonds, and would show a time exponent  $n \sim 0.165$  if the diffusing species is  $\text{H}_2$ , and  $n \sim 0.25$  if it is  $\text{H}^\circ$  [7]. Any intermediate value ( $n \sim 0.2$ ) can be explained by any of the following: 1) a mix of  $\text{H}_2$  and  $\text{H}^\circ$  species, 2)  $\text{H}^\circ$  species plus dispersive transport, and 3)  $\text{H}_2$  species plus recovery due to measurement delay [7]. Independent measurements of the activation energy of diffusion also points to  $\text{H}_2$  species [10], [17]. The  $n \sim 0.3$  time exponent of enhanced  $\Delta N_{IT}$  for  $V_B > 0$  stress is due to the sum of two components: *normal*  $\Delta N_{IT}$  with  $n \sim 0.2$  plus the *additional*  $\Delta N_{IT}$  with  $n \sim 0.5$  (Fig. 1). Note that depending on stress  $V_G$  and  $V_B$ ,  $\Delta N_{IT}$  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,  $\Delta^2 N_{IT}$  always shows a time exponent of  $n \sim 0.5$ .

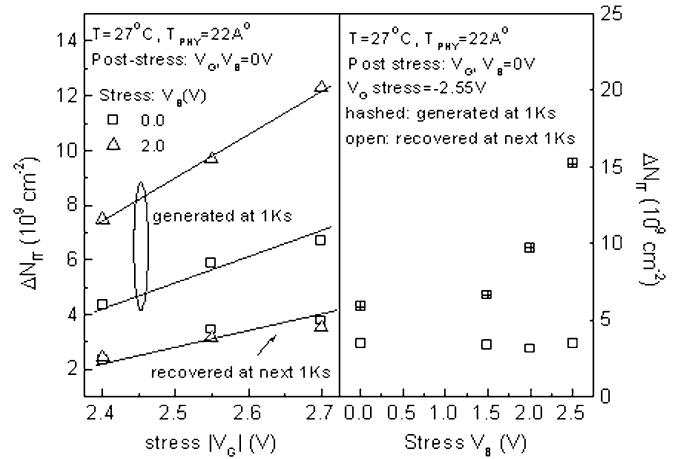


Fig. 2. Interface trap generation at 1000s stress and amount recovered after a subsequent 1000 s post-stress phase. (LHS) For  $V_B = 0$  V and  $V_B = 2$  V stress at different stress  $V_G$ . (RHS) For different stress  $V_B$  at a fixed stress  $V_G$ . Stressing was done on 22 Å p-MOSFETs at  $T =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

The  $n \sim 0.5$  time exponent of  $\Delta^2 N_{IT}$  can be due to (a) broken  $\equiv\text{Si-H}$  bonds followed by release of ionic  $\text{H}^+$  [7], (b) broken  $\equiv\text{Si-O-}$  bonds [13], [20] or (c) both. Note, SILC is always observed together with *additional*  $\Delta N_{IT}$  in the presence of HH, which clearly identifies that  $\equiv\text{Si-O-}$  bonds are broken [20]. Therefore, at least some of *additional*  $\Delta N_{IT}$  is due to broken  $\equiv\text{Si-O-}$  bonds at Si/SiO<sub>2</sub> interface. It remains to be seen if *additional*  $\equiv\text{Si-H}$  bonds are also broken with subsequent release of  $\text{H}^+$ , and whether  $\text{H}^+$  plays some role in breaking  $\equiv\text{Si-O-}$  bonds [21]. To analyze any possible release of  $\text{H}^+$ , the generation and recovery of  $\Delta N_{IT}$  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  $\equiv\text{Si-}$  to form  $\equiv\text{Si-H}$ , thereby reducing  $\Delta N_{IT}$  [7], [8]. However, *no known mechanism* exists for the passivation of broken  $\equiv\text{Si-O-}$  bonds.

Fig. 2 shows  $\Delta N_{IT}$  generation and recovery as a function of stress  $V_G$  (LHS) and stress  $V_B$  (RHS). As shown in Fig. 2 (LHS),  $\Delta N_{IT}$  generation and recovery increases with increase in stress  $V_G$  (for all stress  $V_B$ ). However, *additional*  $\Delta N_{IT}$  generated for  $V_B > 0$  V stress (for all stress  $V_G$ ) does not recover. This becomes clearer from Fig. 2 (RHS), which shows  $\Delta N_{IT}$  generation increases with stress  $V_B$ , but  $\Delta N_{IT}$  recovery is always identical for all stress  $V_B$  (similar to  $V_B = 0$  case). Fig. 3 shows  $\Delta N_{IT}$  generation and recovery as a function of post stress  $V_G$ .  $\Delta N_{IT}$  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*  $\Delta N_{IT}$  generated in the presence of HH does not recover. Therefore, enhanced  $\Delta N_{IT}$  in the presence of HH for  $V_B > 0$  stress is entirely due to *additional* contribution from broken  $\equiv\text{Si-O-}$  bonds at the Si/SiO<sub>2</sub> interface. If  $\text{H}^+$  ions were generated from broken  $\equiv\text{Si-H}$  bonds, a fraction of them should have diffused back to the Si/SiO<sub>2</sub> interface and passivate at least a fraction of the *additional*  $\equiv\text{Si-}$ . Furthermore, the insensitivity of  $\Delta N_{IT}$  recovery to post stress

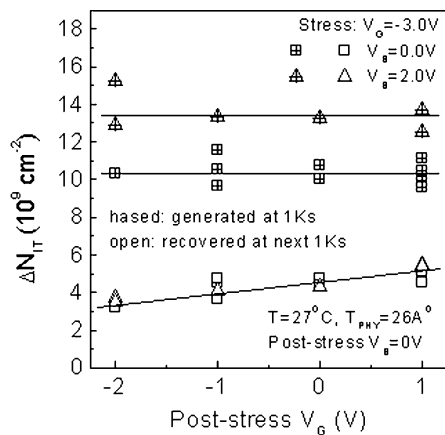


Fig. 3. Interface trap generation for  $V_B = 0$  V and  $V_B = 2$  V stress and its recovery during a subsequent post-stress phase for different post-stress  $V_G$ . Stressing was done on 26 Å p-MOSFETs at  $T = 27^\circ\text{C}$  in inversion. Post-stress  $V_B = 0$  V for all measurements. Lines are 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  $\text{H}^+$  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  $\Delta N_{IT}$  by breaking  $\equiv\text{Si}-\text{H}$  bonds. Released H species move away as neutral  $\text{H}^\circ$  or  $\text{H}_2$ , yield a time power-law with  $n \sim 0.2$ , and come back after stress and anneal a fraction of  $\Delta N_{IT}$  by passivating  $\equiv\text{Si}-\text{H}$  bonds. HH generation and subsequent injection into oxide break  $\equiv\text{Si}-\text{O}-$  bonds, which appears as *additional*  $\Delta N_{IT}$  and  $\Delta N_{OT}$ , show a power-law with  $n \sim 0.5$  and does not recover after stress. Overall  $\Delta N_{IT}$  becomes a sum of normal and *additional*  $\Delta N_{IT}$  components and shows a power-law with  $0.2 < n < 0.5$ . Finally, the lack of evidence of  $\text{H}^+$  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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