

On the Generation and Recovery of Interface Traps in MOSFETs Subjected to NBTI, FN, and HCI Stress

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Abstract—A common framework for interface-trap (N_{IT}) generation involving broken $\equiv\text{Si-H}$ and $\equiv\text{Si-O}$ bonds is developed for negative bias temperature instability (NBTI), Fowler–Nordheim (FN), and hot-carrier injection (HCI) stress. Holes (from inversion layer for pMOSFET NBTI, from channel due to impact ionization, and from gate poly due to anode–hole injection or valence-band hole tunneling for nMOSFET HCI) break $\equiv\text{Si-H}$ bonds, whose time evolution is governed by either one-dimensional (NBTI or FN) or two-dimensional (HCI) reaction–diffusion models. Hot holes break $\equiv\text{Si-O}$ bonds during both FN and HCI stress. Power-law time exponent of N_{IT} during stress and recovery of N_{IT} after stress are governed by relative contribution of broken $\equiv\text{Si-H}$ and $\equiv\text{Si-O}$ bonds (determined by cold- and hot-hole densities) and have important implications for lifetime prediction under NBTI, FN, and HCI stress conditions.

Index Terms—Anode–hole injection (AHI), charge pumping (CP), Fowler–Nordheim (FN), hot-carrier injection (HCI), interface traps (N_{IT}), negative bias temperature instability (NBTI), reaction–diffusion (R–D) model, stress-induced leakage current (SILC), valence-band hole tunneling (VBHT).

I. INTRODUCTION

INTERFACE-TRAP (N_{IT}) generation is an important reliability concern in MOSFETs subjected to negative bias temperature instability (NBTI), Fowler–Nordheim (FN), and hot-carrier injection (HCI) stress [1]–[12]. It is generally believed that N_{IT} generation is due to breaking of $\equiv\text{Si-H}$ bonds at the Si–SiO₂ interface and the resultant production of $\equiv\text{Si-}(N_{IT})$, which show up as P_b centers in electron spin resonance (ESR) studies [13]. The time evolution of N_{IT} shows power-law dependence, with larger value of exponent n for FN and HCI compared with NBTI stress. On the other hand, unlike HCI and FN stress, significant N_{IT} recovery has been observed after NBTI stress [14], [15]. The mechanism of N_{IT} generation during stress and any recovery of N_{IT} after stress must be properly understood and modeled for accurate prediction of device lifetime under actual operating conditions.

It is now believed that inversion-layer (cold) holes are responsible for the breaking of $\equiv\text{Si-H}$ bonds during NBTI stress in pMOSFETs [4]. Classical one-dimensional (1-D) reaction–diffusion (R–D) model [16] can successfully explain N_{IT} generation and recovery characteristics for NBTI stress [17], [18]. R–D model suggests that N_{IT} generation is due to the break-

ing of interfacial $\equiv\text{Si-H}$ bonds and subsequent diffusion of released H species into the oxide bulk. N_{IT} recovery is due to back diffusion of H species toward the Si–SiO₂ interface and repassivation of $\equiv\text{Si-}$. R–D model can explain the (relatively) lower n of N_{IT} generation during NBTI stress as due to release and diffusion of either or both neutral H⁰ and H₂ species [18].

Note that the crucial difference between NBTI and HCI or FN is the presence of hot electrons (HE) and hot holes (HH) for the latter stress conditions [4], [7], [10]. Significant efforts were made in the past to understand whether only electrons, or only holes, or both electrons and holes are responsible for breaking of $\equiv\text{Si-H}$ bonds during HCI and FN stress [5]–[10], [12], [19], [20]. The higher n of N_{IT} generation during uniform FN stress can be explained within the 1-D R–D framework by assuming possible release and subsequent drift of H⁺ species [18]. A two-dimensional (2-D) extension of the classical R–D model, which considers localized (near drain junction) breaking of interfacial $\equiv\text{Si-H}$ bonds and subsequent 2-D diffusion of released H⁰ species, has been proposed to model HCI [21].¹ The model suggests that the spread of HCI degraded region (due to broken $\equiv\text{Si-H}$ bonds) determines n during stress and recovery after stress. However, the above models need experimental validation, and much work is needed to develop a unified model for N_{IT} generation under all stress conditions.

Furthermore, whereas NBTI stress (negligible hot carriers) produce only N_{IT} [4], HCI and FN stress (hot carriers present) also produce bulk traps (N_{OT}) [7], [10]–[12], [23]–[26]. N_{OT} generation is believed to be due to broken $\equiv\text{Si-O}$ bonds at the oxide bulk [24]–[26]. There has been significant debate on whether HH or H⁺ diffusion (following breaking of $\equiv\text{Si-H}$ bonds) break $\equiv\text{Si-O}$ bonds during FN and HCI stress [24], [25], [27], [28]. Broken $\equiv\text{Si-O}$ bonds at oxide bulk give rise to stress-induced leakage current (SILC) [7], [12], [24]–[26], [29], [30],² whereas those at (or near) Si–SiO₂ interface can contribute to overall measured N_{IT} [32]. However, unlike $\equiv\text{Si-H}$ bonds, broken $\equiv\text{Si-O}$ bonds are not known to recover at room temperature after the stress is removed. 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 [33], [34] (and check for the release of H⁺, if any), as these scenarios lead to substantially different lifetime projections for NBTI, FN, and HCI stress. We know of no effort so far that has

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¹Alternatively, the stretched-exponent model [22] also explains power-law dependence of N_{IT} generation.

²An alternative viewpoint [31] for the origin of SILC is the bridging of H⁺ into an existing oxygen vacancy.

successfully differentiated between these two types of N_{IT} generation processes for a wide range of stress conditions.

This paper attempts to develop a common framework for N_{IT} generation and recovery under NBTI, FN, and HCI stress conditions. The contribution of broken $\equiv\text{Si-H}$ and $\equiv\text{Si-O}$ bonds on N_{IT} is explored by varying HE and HH energies under different stress configurations and monitoring N_{IT} buildup and recovery for successive stress and poststress periods. For uniform (NBTI or FN) stress, various combinations of $\equiv\text{Si-H}$ and $\equiv\text{Si-O}$ related defects are created by stressing pMOSFETs at different gate (V_G) and substrate (V_B) voltages. It is shown that when stressed at low V_G ($V_B = 0$) such that HH generation is negligible, ΔN_{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 [4], enhanced ΔN_{IT} is observed. HH-induced additional ΔN_{IT} does not recover and shows a unique power law in time that matches well with that of SILC. It is conclusively shown that additional ΔN_{IT} caused by $V_B > 0$ stress is due to HH-induced broken $\equiv\text{Si-O}$ bonds at the Si-SiO₂ interface.

For nonuniform HCI stress in nMOSFETs, HE and HH densities were varied by carefully designed experiments on devices having different channel length L and oxide thickness T_{PHY} , under different V_G , V_B , and drain (V_D) voltages. The localized HE and HH density distributions under different stress configurations were obtained from full-band Monte Carlo simulations. It is shown that 2-D R-D model (concerning spread of broken $\equiv\text{Si-H}$ bonds) alone is insufficient; contribution due to broken $\equiv\text{Si-O}$ bonds (due to HH) must also be taken into account to explain the generation and recovery of N_{IT} during HCI stress under a wide range of stress conditions. It is also shown that channel HE do not directly break $\equiv\text{Si-H}$ bonds during HCI stress. Holes, originated from impact ionization (II), anode-hole injection (AHI) [25], as well as from valence-band hole tunneling (VBHT) [35] processes break $\equiv\text{Si-H}$ bonds. Hole (not electron)-induced breaking of $\equiv\text{Si-H}$ bonds during nMOSFET HCI stress is consistent with inversion-layer hole-induced breaking of $\equiv\text{Si-H}$ bonds for pMOSFET NBTI stress [4]. Based on relative contribution of $\equiv\text{Si-H}$ and $\equiv\text{Si-O}$ bonds, HCI degradation of devices is explored as supply V_{DD} is scaled. Our results have important implications for selecting stress voltages, projection of device lifetime under variety of operating conditions, and modeling of N_{IT} generation and recovery by 1-D and 2-D R-D models.

II. EXPERIMENTAL RESULTS

Experiments were performed at $T = 27^\circ\text{C}$ on n- and p-channel MOSFETs having (nonnitrided) gate oxides with T_{PHY} of 22, 24, 26, and 48 Å and L of 0.20 and 0.28 μm (width $W = 10\ \mu\text{m}$). Uniform FN (or NBTI) stress was applied in pMOSFETs at different V_G and V_B . Nonuniform HCI stress was applied in nMOSFETs under different V_G , V_B , and V_D . FN (or NBTI) and HCI stress were followed by poststress periods with all terminals grounded (unless specifically mentioned otherwise). Both the stress and poststress periods were periodically interrupted to estimate N_{IT} by measuring charge pumping (CP) current I_{CP} [36], using a single-level pulse at frequency

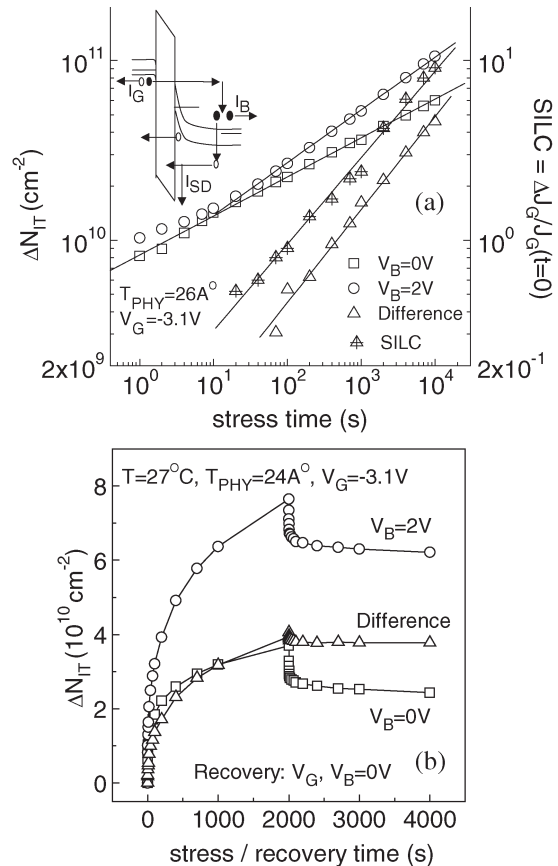


Fig. 1. (a) Time evolution of N_{IT} generation for uniform NBTI and FN stress at different V_B but fixed V_G . $V_B > 0$ stress-induced enhanced N_{IT} and SILC are also shown. SILC was measured at $V_G = -2.5\ \text{V}$. Inset shows pMOSFET energy band under $V_B > 0$ stress. (b) Time evolution of N_{IT} generation and recovery during and after uniform stress at different V_B but fixed V_G .

$f = 800\ \text{kHz}$. The delay (stress-off time) for measurement was fixed at 500 ms. Note that the value of n obtained in the presence of measurement delay is slightly higher than the true value due to unintentional recovery effects (where applicable) as explained in [14] and [15]. As degradation is uniform along the channel, ΔN_{IT} ($= \Delta I_{CP}/qfWL$) can be easily determined for FN or NBTI stress. Determination of ΔN_{IT} is difficult due to the nonuniform localized nature of HCI damage. Although it is possible to determine the spatial profile of HCI damage [11], [23], it is outside the scope of this work. Therefore, FN degradation is expressed in terms of ΔN_{IT} , whereas HCI degradation is expressed in terms of ΔI_{CP} . 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 sweeps) to nullify any charge-trapping-induced transient effects [37].

A. Uniform FN Stress Experiments in pMOSFETs

Fig. 1(a) shows the time evolution of N_{IT} for FN (or NBTI) stress under different V_B but constant V_G . Increasing V_B stress was used to generate increasing amount of HH in the channel by II, as depicted using the energy band diagram shown in the inset of Fig. 1(a). ΔN_{IT} shows power-law time dependence, with lower n for stress at $V_B = 0$. ΔN_{IT} increases with HH

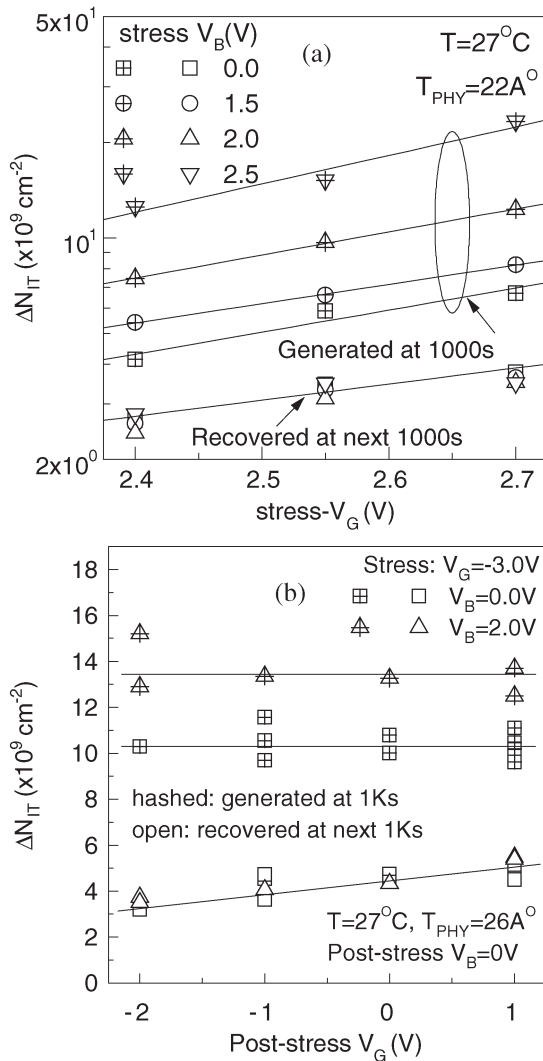


Fig. 2. N_{IT} generation after 1000-s uniform NBTI and FN stress and recovered after subsequent 1000-s poststress phase. (a) For different stress V_G and V_B but fixed (zero) poststress V_G . (b) For different stress V_B and poststress V_G but fixed stress V_G . Poststress $V_B = 0$.

energy as stress V_B is increased, and the power-law signature is maintained although with a higher value of n . Note that the time beyond which $V_B > 0$ stress-induced ΔN_{IT} enhancement shows up reduces as V_B is increased. Time evolution of $V_B > 0$ stress-induced additional ΔN_{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(a). Additional ΔN_{IT} and SILC were observed only for $V_B > 0$ stress under significant HH generation; both show good correlation with quantum yield [38] of HH generation as V_B is increased (not shown) [4] and show power-law time dependence with very similar n . Fig. 1(b) shows the generation and recovery of ΔN_{IT} after stress under different V_B but constant V_G . The absolute magnitude of ΔN_{IT} recovery does not change with stress V_B , which implies that additional ΔN_{IT} generated due to $V_B > 0$ stress is “permanent” and does not recover after removal of stress.

Fig. 2(a) shows ΔN_{IT} generation and recovery for different V_G and V_B stress. It can be seen that ΔN_{IT} generation increases with increase in both V_G and V_B during stress. However,

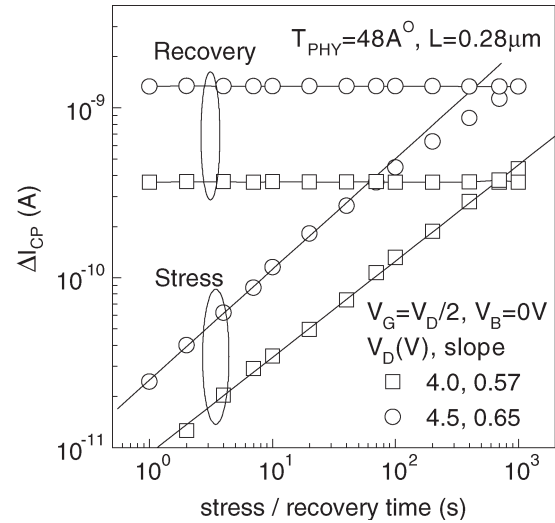


Fig. 3. Stress V_D dependence of time evolution of ΔI_{CP} ($\sim \Delta N_{IT}$) generation and recovery for 1000 s of HCI stress and poststress phases. Stress $V_G = V_D/2$, $V_B = 0$. All terminals were grounded during poststress.

increase in recovery is only seen following stress at increased stress V_G . Additional ΔN_{IT} generated for $V_B > 0$ stress does not recover (identical recovery is seen for stress with different V_B for all stress V_G). Fig. 2(b) shows ΔN_{IT} generation for $V_B = 0$ and $V_B > 0$ (fixed V_G) stress, and recovery for different poststress V_G . ΔN_{IT} recovery is always identical for both $V_B = 0$ and $V_B > 0$ stress for all poststress V_G (once again, additional ΔN_{IT} due to $V_B > 0$ stress does not recover) and is only “weakly” dependent on the sign and magnitude of poststress V_G .

B. Nonuniform HCI Stress Experiments in nMOSFETs

Fig. 3 shows the time evolution of ΔI_{CP} ($\sim \Delta N_{IT}$) generation and recovery for different V_D ($V_G = V_D/2$, $V_B = 0$, and fixed L and T_{PHY}) stress. The usual power-law time dependence is seen but with much larger n compared with that for FN or NBTI stress (Fig. 1). Both the magnitude and n increase with increasing stress V_D . Long-time saturation seen at higher degradation level is due to reduction in drain current (and hence stress level). Unlike FN stress, ΔN_{IT} does not recover (at all) after the removal of stress, which is true for all V_D (and all L , shown later) under these stress conditions.

Fig. 4(a) shows the time evolution of ΔI_{CP} ($\sim \Delta N_{IT}$) generation for $V_G = V_D/2$ stress under different V_B and on devices with different L (V_D and T_{PHY} fixed). Once again, power-law time dependence is seen for all stress conditions, and the saturation observed for higher degradation level is due to the reduction in stress level. The magnitude of ΔI_{CP} increases with higher $|V_B|$ and lower L . However, n decreases with higher $|V_B|$ but is insensitive to reduction in L . Fig. 4(b) shows the time evolution of ΔI_{CP} recovery after different stress conditions ($V_G = V_D/2$ and different V_B and L). Recovery is not seen after $V_B = 0$ stress, irrespective of L [similar to Fig. 3(b)]. Recovery is only seen after $V_B < 0$ stress, and both fractional and absolute recovery increase with increase in $|V_B|$. The fractional recovery remains the same, whereas the absolute recovery increases as L is scaled.

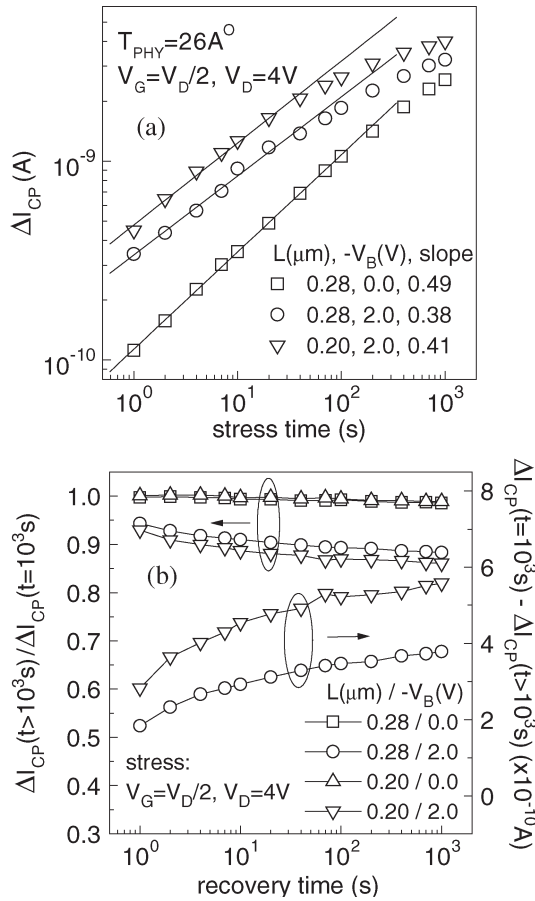


Fig. 4. Impact of L scaling on (a) time evolution of ΔN_{IT} ($\sim \Delta I_{CP}$) generation during HCI stress at different V_B (b) fractional and absolute recovery after stress. Stress $V_G = V_D/2$, V_D fixed. All terminals were grounded during poststress.

Fig. 5(a) shows the time evolution of ΔI_{CP} ($\sim \Delta N_{IT}$) generation for different stress V_G and on devices having different T_{PHY} (V_D , V_B , and L fixed). Once again, power-law behavior is observed, with a reduction in n at higher V_G ($= V_D$). Moreover, although ΔI_{CP} magnitude increases, n shows a drastic reduction for $V_G = V_D$ stress as T_{PHY} is scaled below the direct tunneling limit. Fig. 5(b) shows the time evolution of fractional ΔI_{CP} recovery after different conditions of stress as Fig. 5(a). For $V_B = 0$, recovery is not observed after $V_G = V_D/2$ stress. Recovery is seen after $V_G = V_D$ ($V_B = 0$) stress, which drastically increases as T_{PHY} is scaled.

III. SIMULATION RESULTS AND EXPLANATIONS

A. Uniform FN Stress Experiments in *p*MOSFETs

Note that FN stress with $V_B = 0$ (negligible HH) is the normal NBTI stress, where ΔN_{IT} is known to be due to breaking of $\equiv\text{Si}-\text{H}$ bonds at the $\text{Si}-\text{SiO}_2$ interface (the exact microscopic mechanism is unknown) and subsequent movement of released H into the oxide, which leaves behind $\equiv\text{Si}-(N_{IT})$. As per the solution of 1-D R-D model for NBTI [16], ΔN_{IT} would show a power-law behavior with time exponent $n \sim 0.165$ if the diffusing species is H_2 and $n \sim 0.25$ if it is H° [18]. Any intermediate value ($n \sim 0.2$) can be explained by any of the

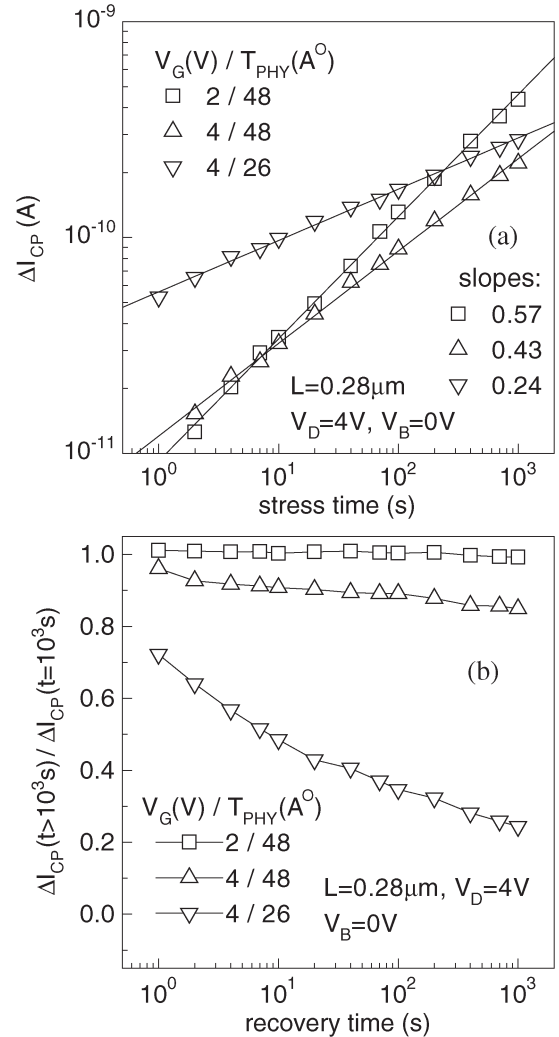


Fig. 5. (a) Time evolution of ΔN_{IT} ($\sim \Delta I_{CP}$) generation for HCI stress at different V_G , V_B , and T_{PHY} . V_D constant for all stress configurations. (b) Fractional recovery of ΔI_{CP} following stress at different V_G , V_B , and T_{PHY} . All terminals were grounded during poststress.

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 [14], [15]. Independent measurements of the activation energy of diffusion points to the diffusion of H_2 species [4], [39] and, therefore, $n \sim 0.2$ is likely due to (3). 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 $n \sim 0.5$, as shown in Fig. 1(a). Depending on stress V_G and V_B , ΔN_{IT} for $V_B > 0$ stress shows a wide range of n [40] based on the relative magnitude of normal and additional components (not shown).

The $n \sim 0.5$ time exponent of $\Delta^2 N_{IT}$ can be due to 1) broken $\equiv\text{Si}-\text{H}$ bonds followed by release and drift of H^+ as per the solution of 1-D R-D model [18], 2) broken $\equiv\text{Si}-\text{O}$ bonds at or near the $\text{Si}-\text{SiO}_2$ interface [24]–[26], or 3) both. Note that SILC is always observed together with additional ΔN_{IT} in the presence of HH, which clearly identifies that $\equiv\text{Si}-\text{O}$ bonds are broken [26], [29]. Hence, at least a fraction of additional ΔN_{IT} is due to broken $\equiv\text{Si}-\text{O}$ bonds at $\text{Si}-\text{SiO}_2$ interface. It remains to be seen if additional $\equiv\text{Si}-\text{H}$ bonds

are also broken with subsequent release of H^+ , and whether H^+ diffusion plays some role in breaking $\equiv Si-O$ bonds [27], [28], [30].

Note that 1-D R-D model also predicts that once stress is removed, some of the released H species come back to the interface and rapidly re-passivate $\equiv Si-$ to form $\equiv Si-H$, thereby reducing ΔN_{IT} [16]–[18]. However, any recovery of broken $\equiv Si-O$ bonds at room temperature is not known. Fig. 1(b) shows that a fraction of ΔN_{IT} generated during $V_B = 0$ and $V_B > 0$ stress recovers after stress. However, additional ΔN_{IT} generated in the presence of HH for $V_B > 0$ stress does not recover after stress, and this is true for a wide range of stress V_G and V_B as shown in Fig. 2(a). Therefore, enhanced ΔN_{IT} in the presence of HH for $V_B > 0$ stress is entirely due to additional contribution from broken $\equiv Si-O$ bonds at the $Si-SiO_2$ interface. If H^+ ions were released and diffused from broken $\equiv Si-H$ bonds, a fraction of them should have diffused back to the $Si-SiO_2$ interface and passivate at least a fraction of the additional $\equiv Si-$. This would have resulted in larger recovery after $V_B > 0$ stress, contrary to observed results. Identical post- V_G dependence of recovery as shown in Fig. 2(b) suggests similar diffusion species for both $V_B = 0$ and $V_B > 0$ stress. The time exponent of $n \sim 0.2$ during $V_B = 0$ stress and the insensitivity of ΔN_{IT} recovery to poststress V_G can only be explained if the diffusing H species is always neutral.

Therefore, N_{IT} generation has two different origins due to broken $\equiv Si-H$ and $\equiv Si-O$ bonds. When HH generation is insignificant, N_{IT} is due to broken $\equiv Si-H$ bonds at the $Si-SiO_2$ interface and subsequent diffusion of H_2 , a fraction of which recovers after stress. Additional $\equiv Si-H$ bonds can get broken in the presence of HH. However, because HH density is much less than that of inversion-layer (cold) holes, HH-induced broken $\equiv Si-H$ bonds would be insignificant compared with $\equiv Si-H$ bonds broken by cold holes. No evidence is observed for diffusion of H^+ when HH is absent or present. In the presence of large HH generation, broken $\equiv Si-O$ bonds at or very close to the $Si-SiO_2$ interface also makes an additional contribution and increases the overall magnitude and power-law time exponent n of measured N_{IT} . Unlike broken $\equiv Si-H$ bonds, broken $\equiv Si-O$ bonds do not recover after stress. However, the exact microscopic mechanism of how inversion-layer cold holes break $\equiv Si-H$ bonds and HH breaks $\equiv Si-O$ bonds is not yet understood and calls for further (microscopic) modeling and analysis.

B. Nonuniform HCI Stress Experiments in nMOSFETS

As mentioned in Section I, the correlation of n and fractional recovery for HCI stress has been predicted by the 2-D R-D model [21]. It was proposed that larger spread of the degraded (broken $\equiv Si-H$ bonds) region would produce lower n and larger recovery during stress and poststress phases, respectively. Note that the model does not comment on any N_{IT} contribution due to broken $\equiv Si-O$ bonds at (or very close to) the $Si-SiO_2$ interface [32] and does not predict $n > 0.5$. To verify whether HCI results can be explained by 2-D R-D model, process, device, and full band Monte Carlo simulations were performed using well-calibrated DIOS, DESSIS [41], and SMC [42] sim-

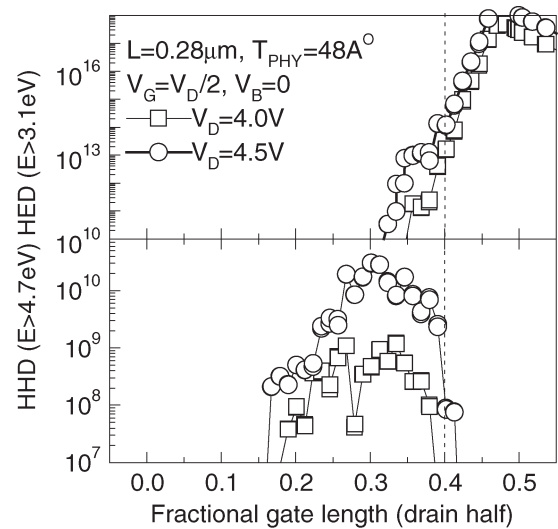


Fig. 6. Spatial distribution of simulated HE and HH densities along the channel and at the $Si-SiO_2$ interface under different V_D . All conditions similar to Fig. 3. $x = 0$ corresponds to the center of channel, whereas $x = 0.5$ corresponds to the gate edge on the drain side.

ulators. Note that for the devices used in this study, CP measurement probes the drain half of the channel, from the center up to a fractional length (L_F) of about 0.4 [11], [23]. Therefore, HE and HH density distributions up to $L_F = 0.4$ should be used to interpret the experimental results.

Fig. 6 shows simulated HE and HH profiles for different stress V_D ($V_G = V_D/2$, $V_B = 0$, and fixed T_{PHY} and L). The HE and HH spread shows very little increase, whereas HH peak increases by a large amount as V_D is increased. The observed $n > 0.5$ time exponent and increase in n with increase in V_D cannot be explained by 2-D R-D model based on localized broken $\equiv Si-H$ bonds. These results can only be explained if increased contribution from broken $\equiv Si-O$ bonds (due to increased HH density at higher V_D) is assumed. No recovery observed after the removal of stress also suggests that for $V_G = V_D/2$, $V_B = 0$ stress (on relatively thicker T_{PHY} devices), broken $\equiv Si-O$ bonds dominate N_{IT} contribution. Any contribution due to $\equiv Si-H$ bonds (by HE and/or by holes out of II) must be insignificant or highly localized to have zero recovery after stress. However, as mentioned before, the connection between HH density and breaking of $\equiv Si-O$ bond is yet unclear and needs attention.

Fig. 7 shows HE and HH profiles for different stress V_B and L ($V_G = V_D/2$, and fixed V_D and T_{PHY}). The spread of HE distribution increases with higher $|V_B|$ and lower L , whereas the peak and spread of HH distribution remain unaffected at higher $|V_B|$ and increases by a large amount at lower L . Inasmuch as $V_B < 0$ stress does not impact HH density, non-recoverable $\equiv Si-O$ contribution remains unchanged between $V_B = 0$ and $V_B < 0$ stress. However, the spread of II [42], [43] (not shown) and HE distribution (shown) increase as V_B is made negative and so is the spread of broken $\equiv Si-H$ bonds (assuming impact ionized holes and/or HE breaks $\equiv Si-H$ bonds). Therefore, 2-D R-D model in principle can explain lower n and larger fractional as well as absolute recovery observed for $V_B < 0$ stress.

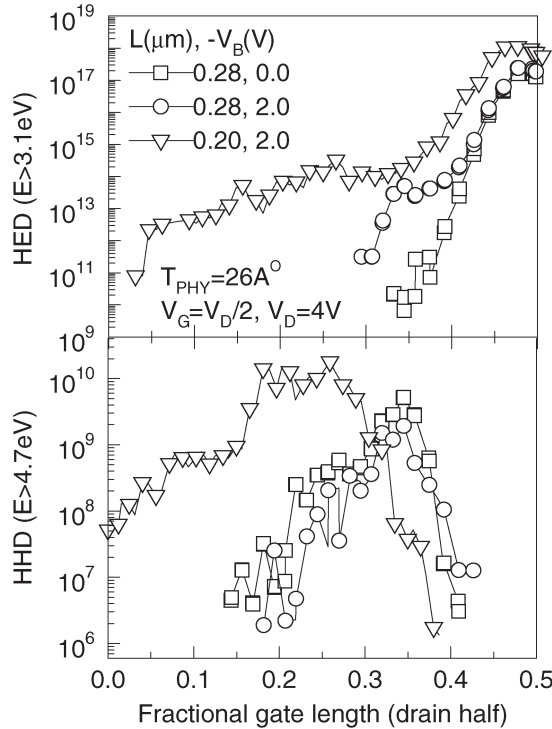


Fig. 7. Spatial distribution of simulated HE and HH densities along the channel and at the Si-SiO₂ interface under different L and V_B . All conditions similar to Fig. 4. $x = 0$ corresponds to the center of channel, whereas $x = 0.5$ corresponds to the gate edge on the drain side.

Note that both II (not shown) and HE spread also increase as L is scaled. A naive application of 2-D R-D model as above would suggest reduced n and larger recovery as L is scaled. This is contrary to the experimental result (no change in n as L is scaled, see Fig. 4). Therefore, additional contribution due to broken $\equiv\text{Si}-\text{O}$ bonds must be considered. Both the peak and spread of HH distribution increase as L is scaled, which would suggest increased $\equiv\text{Si}-\text{O}$ contribution. Increased II and HE spread at lower L would also imply increased $\equiv\text{Si}-\text{H}$ contribution. In general, n can either reduce or increase as L is scaled, depending on the relative increase of $\equiv\text{Si}-\text{H}$ and $\equiv\text{Si}-\text{O}$ contributions. For the present case, no change in n implies similar increase in $\equiv\text{Si}-\text{H}$ and $\equiv\text{Si}-\text{O}$ contributions as L is scaled. Moreover, because higher N_{IT} generation at lower L is contributed by both $\equiv\text{Si}-\text{H}$ (recoverable) and $\equiv\text{Si}-\text{O}$ (nonrecoverable), fractional recovery remains almost the same, whereas absolute recovery increases (following a $V_B < 0$ stress) as L is scaled and can explain the observed results.

It is clear from the above discussion that HH breaks $\equiv\text{Si}-\text{O}$ bonds and either HE and/or impact ionized (not necessarily hot) holes break $\equiv\text{Si}-\text{H}$ bonds, both of which determine the time exponent and recovery fraction during and after stress, respectively. Although the role of HH behind broken $\equiv\text{Si}-\text{O}$ bonds is clearly established (the exact mechanism that governs the power-law time exponent is yet unknown), it is not clear so far whether either or both HE and impact ionized holes break $\equiv\text{Si}-\text{H}$ bonds.

Fig. 8 shows HE profile as V_G is increased and T_{PHY} is scaled (fixed V_D , V_B , and L). Note that HE spread does

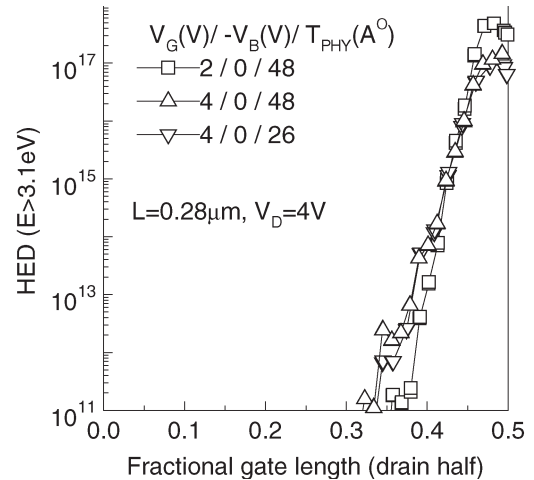


Fig. 8. Spatial distribution of simulated HE density along the channel and at the Si-SiO₂ interface under different stress V_G , V_B , and T_{PHY} . All conditions similar to Fig. 5. $x = 0$ corresponds to the center of channel, whereas $x = 0.5$ corresponds to the gate edge on the drain side.

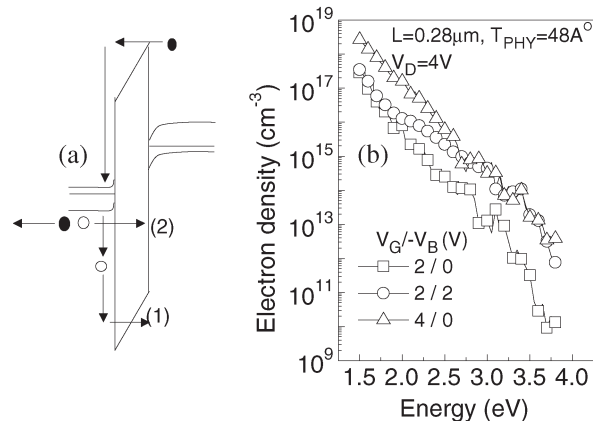


Fig. 9. (a) Energy band diagram for nMOSFET in inversion showing 1) AHI and 2) VBHT processes. (b) Simulated EED for different stress V_G and V_B . Data were extracted at the Si-SiO₂ interface and at the point of maximum electron injection.

not increase at higher V_G and lower T_{PHY} . Moreover, II and HH density become insignificant for $V_G = V_D$ stress (for all T_{PHY}). Dominant HH generation can explain $n > 0.5$ slope and negligible recovery for $V_G = V_D/2$, $V_B = 0$ stress (thicker T_{PHY}). The absence of recovery under such condition implies negligible or highly localized (HE or impact ionized hole induced) broken $\equiv\text{Si}-\text{H}$ bonds. As HE spread does not significantly increase from $V_G = V_D/2$ to $V_G = V_D$ stress, absence of HH-induced broken $\equiv\text{Si}-\text{O}$ bonds for $V_G = V_D$ stress alone cannot explain observed reduction in n and higher recovery. Furthermore, in spite of no change in HE spread, n reduces and recovery increases drastically as T_{PHY} is scaled. Therefore, the observed changes in n and fractional recovery for varying stress V_G and T_{PHY} cannot be explained by 2-D R-D model if one assumes HE breaks $\equiv\text{Si}-\text{H}$ bonds and HE spread equals the spread of broken $\equiv\text{Si}-\text{H}$ bonds.

Note that for nMOSFET HCI stress, holes can also reach Si-SiO₂ interface via AHI [25] and VBHT [35] processes (under favorable oxide field), as shown using the energy band diagram of Fig. 9(a). Fig. 9(b) plots the electron energy

distribution (EED) at the Si–SiO₂ interface and at a point of maximum electron injection for various stress conditions. Compared with $V_G = V_D/2$, $V_B = 0$, both $V_G = V_D/2$, $V_B < 0$ as well as $V_G = V_D$, $V_B = 0$ stress increase the population of high energy tail of EED. Higher HE spread and higher EED tail would increase gate current (I_G) for $V_G = V_D/2$, $V_B < 0$ stress [43]. Higher EED tail and higher spatial area of favorable oxide field would increase I_G for $V_G = V_D$, $V_B = 0$ stress. Increase in electron gate current would increase AHI for these conditions. By assuming lateral spreading of injected electrons inside the gate poly, back-injected holes due to AHI would reach the Si–SiO₂ interface over a wider area. Furthermore, as T_{PHY} is reduced below the direct tunneling limit, increased VBHT would cause holes to reach the Si–SiO₂ interface more uniformly over an even wider area.

We propose that even for HCI stress, \equiv Si–H bonds are broken by holes (and not by electrons), consistent with hole-induced mechanism observed for NBTI stress. For $V_G = V_D/2$ stress, broader II area [43] and larger AHI would produce larger spread of broken \equiv Si–H bonds for $V_B < 0$. Even if HE spread remains constant and II reduces with increase in $V_G (= V_D)$, increase in AHI over a wider area in the channel causes larger spread of broken \equiv Si–H bonds. As T_{PHY} is scaled below the direct tunneling limit, holes due to VBHT create a very wide spread of broken \equiv Si–H bonds. Now, it is possible to explain the reduction in n during stress and increase in fractional recovery after stress for higher stress $|V_B|$ and V_G and lower T_{PHY} within the 2-D R–D model framework.

Fig. 10 summarizes the parameter dependence of \equiv Si–H and \equiv Si–O contribution and its effect on n and recovery for HCI stress. For $V_G = V_D/2$, $V_B = 0$, increased n and no recovery as V_D is increased is due to increased \equiv Si–O contribution due to increased HH density. As V_G is increased to $V_G = V_D$, n reduces and recovery increases due to reduction in \equiv Si–O contribution (negligible HH) and increased \equiv Si–H contribution over a larger spread due to increased AHI. On the other hand, for $V_B < 0$ ($V_G = V_D/2$), increased II area and increase in AHI cause broken \equiv Si–H over a wider spread, resulting in further reduction in n and increased recovery. Increased VBHT as T_{PHY} is scaled reduces n and increases recovery by an even larger extent. Finally, II, HH generation, and AHI (due to HE) increase as L is scaled. Hence, relative increase of \equiv Si–H (due to holes from II and AHI) and \equiv Si–O (due to HH) contribution determines overall n and fractional recovery, whereas absolute recovery always increases as L is scaled. Fig. 10 also shows the prevalence of different physical mechanisms and their effect as V_G is switched from 0 to V_D . For $V_B = 0$, peak substrate current (I_B) stress breaks mostly \equiv Si–O bonds (HH), and any broken \equiv Si–H bonds must be negligible or highly localized. Therefore, large n and no recovery are seen. However, for $V_B < 0$, peak I_B stress breaks both \equiv Si–O and \equiv Si–H (II and AHI). Therefore, n reduces and some recovery is seen. As HH generation is negligible, peak gate current I_G stress generates only \equiv Si–H (AHI and VBHT), and lower n and higher recovery fraction are observed.

Fig. 11 shows peak HH density for $V_G = V_D/2$ stress and peak HE density for both $V_G = V_D/2$ and $V_G = V_D$ stress simulated for different stress V_D . It can be clearly seen that V_D

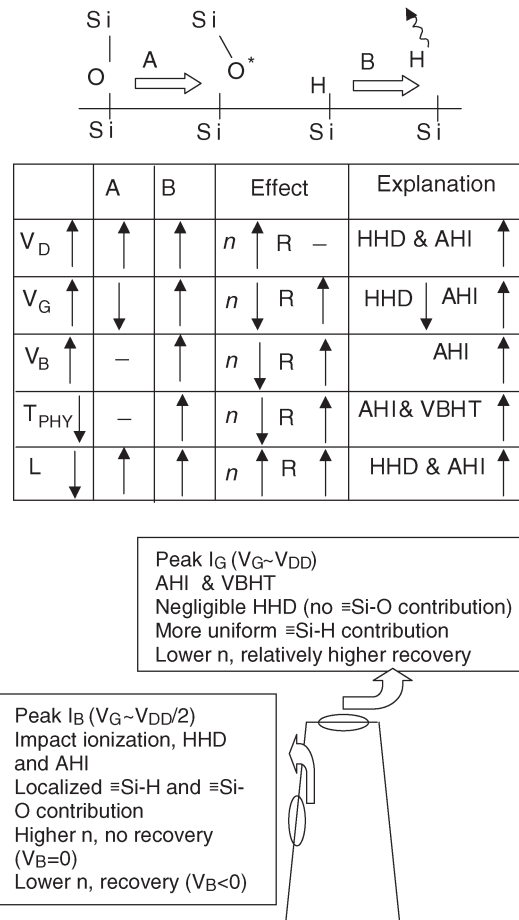


Fig. 10. Summary of HCI results and physical mechanisms that influence power-law time exponent of N_{IT} generation and N_{IT} recovery under different stress and device variables. Various degradation mechanisms operating at peak I_B and peak I_G stress conditions are also shown.

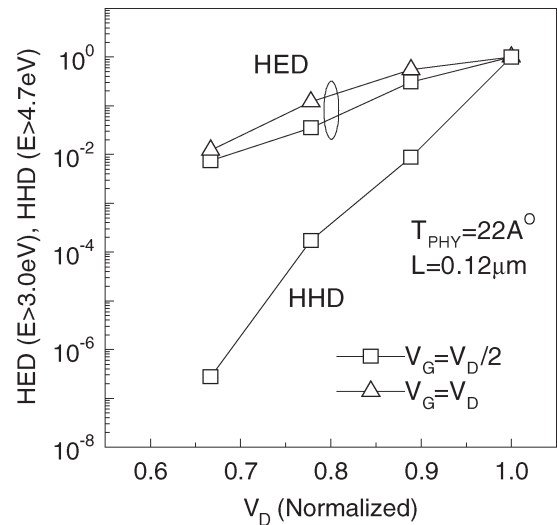


Fig. 11. Simulated peak HE density ($V_G = V_D/2$, $V_G = V_D$) and peak HH density ($V_G = V_D/2$) for different stress V_D ($V_B = 0$). Data normalized for easy reference.

scaling results in much larger relative reduction in peak HH density compared with peak HE density (hence AHI). Moreover, VBHT should also increase as T_{PHY} is scaled. Therefore,

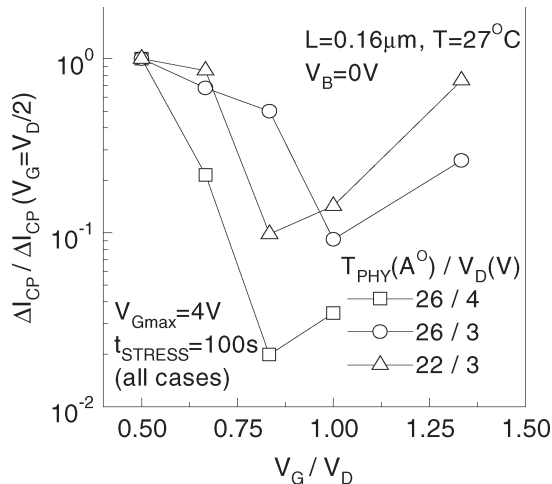


Fig. 12. Generated ΔI_{CP} ($\sim \Delta N_{IT}$) as a function of stress V_G/V_D as V_G is varied for different V_D and T_{PHY} . ΔI_{CP} normalized to the $V_G = V_D/2$ value for easy reference.

as V_D and T_{PHY} are scaled (as a consequence of L scaling), it is expected that $\equiv\text{Si}-\text{O}$ contribution at peak I_B stress would reduce more in comparison with $\equiv\text{Si}-\text{H}$ contribution for peak I_G stress. Therefore, peak I_G stress would show significant N_{IT} compared with peak I_B stress. Fig. 12 shows normalized (to that at $V_G = V_D/2$ stress) ΔI_{CP} as a function of stress V_G/V_D as V_G is varied for a given V_D and T_{PHY} . As V_G is increased relative to $V_G = V_D/2$ stress, ΔI_{CP} first reduces but then increases for larger V_G values due to larger AHI and VBHT. The relative increase of ΔI_{CP} at higher V_G is more for lower stress V_D (more reduction in HH-induced broken $\equiv\text{Si}-\text{O}$ bonds) and lower T_{PHY} (more increase in VBHT-induced broken $\equiv\text{Si}-\text{H}$). This is consistent with the above prediction.

IV. CONCLUSION

To summarize, this paper studies the composition of generated N_{IT} during NBTI, FN, and HCI stress. In the absence of HH for NBTI stress in pMOSFETs, inversion-layer (cold) holes cause N_{IT} generation by breaking $\equiv\text{Si}-\text{H}$ bonds. Released H moves away from the Si-SiO₂ interface as neutral H₂ and governs the time evolution of N_{IT} buildup, which shows a power law with relatively lower value of time exponent n . A fraction of H₂ moves back to the interface and passivates broken $\equiv\text{Si}-$, causing some recovery of generated N_{IT} after stress. For uniform FN stress when HH generation and injection into the oxide is significant, broken $\equiv\text{Si}-\text{O}$ bonds (via yet unknown mechanism) also contributes to N_{IT} , which show a power law with larger n and does not recover after stress. The sum of broken $\equiv\text{Si}-\text{H}$ and $\equiv\text{Si}-\text{O}$ components governs the overall N_{IT} generation and recovery characteristics. No evidence has been found for the release of H⁺ following breaking of $\equiv\text{Si}-\text{H}$ bonds even in the presence of HH during stress.

For nonuniform HCI stress in nMOSFETs, relative contribution of broken $\equiv\text{Si}-\text{H}$ and $\equiv\text{Si}-\text{O}$ bonds also determines N_{IT} generation and recovery characteristics. Broken $\equiv\text{Si}-\text{O}$ bonds exist mostly during peak I_B ($V_G = V_D/2$) stress, cause increase in n and do not recover after stress,

depend on 2-D HH distribution (verified by full-band Monte Carlo simulations), increase at lower L and higher V_D , remain constant as V_B is varied, and disappear for peak I_G ($V_G = V_D$) stress. Broken $\equiv\text{Si}-\text{H}$ bonds exist for both peak I_B (only for $V_B < 0$) and peak I_G stress, cause reduction in n and a fraction recover after stress (depends on spatial spread), and increase with higher $|V_B|$, V_G , and lower T_{PHY} . Broken $\equiv\text{Si}-\text{H}$ bonds do not directly depend on 2-D HE distribution, but rather on distribution of holes coming from II and AHI and VBHT for various stress conditions. Due to significant contribution of broken $\equiv\text{Si}-\text{O}$ bonds, the lateral spread of broken $\equiv\text{Si}-\text{H}$ bonds alone cannot explain all the observed HCI behavior as is expected by the 2-D R-D model. However, the exact mechanism of HH-induced breaking of $\equiv\text{Si}-\text{O}$ bonds needs to be quantified. Moreover, the hole (not electron)-induced breaking of $\equiv\text{Si}-\text{H}$ bonds during HCI stress is also consistent with that observed during NBTI stress.

As V_D and T_{PHY} are scaled (as a consequence of L scaling), it is shown that peak I_G stress and contribution due to broken $\equiv\text{Si}-\text{H}$ bonds would show progressively significant contribution. Finally, we speculate that ultrathin T_{PHY} nMOSFETs in CMOS inverter configuration would show (pMOSFET NBTI-like) positive bias temperature instability (PBTI) phenomenon triggered by VBHT from gate poly, with time exponent similar to pMOSFET NBTI effect. This requires further investigation.

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