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Negative-Bias Temperature Instability – Insight from Recent Dynamic Stress Experiments

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The purpose of this paper is to summarize key experimental evidences on the important role of hole trapping on negative-bias temperature instability (NBTI). For a long time, the focus of this research topic had been on interface degradation driven by hydrogen transport and hole trapping was regarded as a side effect arising out of fast measurement techniques proposed to mitigate the effect of recovery on measurement data. In recent studies, we showed that the threshold voltage (V_t) fluctuations one typically observed under dynamic NBTI were mainly the result of hole trapping and not hydrogen-transport driven interface-state generation/passivation proposed earlier. In particular, the cyclical V_t shifts and constant V_t recovery are inconsistent with the basic principle of the hydrogen transport model. Such behaviors are better described in terms of hole trapping/detrapping at pre-existing oxide defects. We have also shown that interface degradation during NBTI stressing has no apparent impact on bulk (oxide) trap generation, i.e. interface trap generation does not lead to bulk trap generation. This result raises further questions on the validity of the hydrogen transport mechanism and the long standing hypothesis on hydrogen-induced bulk trap generation and gate oxide breakdown. Finally, it is shown that the transient hole trapping responsible for the V_t shift fluctuations could be transformed into more permanent trapped holes under NBTI stressing. The extent of transformation is accelerated by a high oxide field and temperature. An excellent correlation with stress induced leakage current indicates that such transformation underlie the generation of bulk traps reported by earlier studies.

Introduction

Negative-bias temperature instability (NBTI) is one of the most crucial front-end reliability issues of advanced complementary metal-oxide-semiconductor (MOS) technology. The reasons for its importance are threefold: 1) Scaling of the gate oxide thickness has led to a substantial increase of the oxide field E_{ox} . NBTI is found to exhibit a power-law dependence on the oxide field ($\sim E_{ox}^3$) (1), which makes this issue especially critical for the ultrathin gate p-channel MOS field-effect transistor (p-MOSFET). 2) The introduction of nitrogen into the gate oxide to suppress boron penetration (from the p^+ polysilicon gate) and gate tunneling current. NBTI of the oxynitride gate p-MOSFET is shown to be significantly worse than that of the SiO_2 gate p-MOSFET (2) and this is believed to be due to a higher density of nitrogen-related hole traps in the oxynitride (3). 3) The adoption of high dielectric-constant or high-k gate oxides and alternative channel

materials (e.g. Ge, GaAs, etc.) to sustain Moore's law scaling in future technology nodes. The interface quality in these gate stacks is inherently poorer than that of the SiO₂/Si, thus making NBTI an even more critical problem for these novel gate stack technologies.

In spite of the long history of NBTI (known since the inception of the MOS technology in the 1960's), a complete understanding of the mechanism remains elusive, even for the conventional oxynitride (SiON) gate p-MOSFET. One of the main reasons for the lack of understanding is the substantial "black-out" period (~1977-1999) during which research activities were practically non-existent. Before the dual gate technology in early 2000's, the NBTI problem was largely mitigated by the *buried* p-channel, in which the inversion holes (main culprit) were situated away from the oxide interface. Moreover, the apparent success of the reaction-diffusion (R-D) model (4), (5) gave the impression that the basic physics of NBTI was already understood. Indeed, NBTI virtually became synonymous with the R-D model and research effort following the revival of interest in the early 2000's was mostly focused on addressing inconsistencies that arose from the introduction of fast measurement techniques. For instance, the small time-exponent (typically less than 0.1) of as-measured drift curve was ascribed to the parasitic hole trapping effect. It was argued that consistency with the R-D model could be maintained by excluding the parametric shift contributed by hole trapping (6), (7).

Only until very recently did studies convincingly reveal that it was hole trapping and not hydrogen transport that dominated the NBTI recovery observed under pulsed gate condition (8)-(22). The purpose of this paper is to present a brief review of recent results from dynamic stress experiments showing "non R-D" characteristics of NBTI (8), (10). Specifically, we discuss evidence of a cyclical behavior of threshold voltage (V_t) shift, which implies that it is hole trapping and detrapping by a given group of pre-existing oxide defects, and not the transport of hydrogen to and from the oxide/Si interface, that determine dynamic NBTI. We also summarize evidence which shows no apparent relationship between interface and bulk trap generation under NBTI stressing (19), in contrary to the hypothesis that ascribes bulk trap generation to hydrogen species released from the interface degradation or Si-H bond dissociation process (23), (24). This will be followed by a summary of results showing the transformation of transient hole trapping into more permanent trapped holes and its role on bulk trap generation (14), (16), (18), (20)-(22).

Non R-D Characteristics of NBTI Recovery

Some authors argued that NBTI was consistent with the R-D model after excluding the hole trapping effect (assumed to dominate the initial degradation and saturate after ~1 s of stressing) (6), (7). This was based primarily on the ability to reproduce a power-law exponent of 1/6 for the "corrected" drift curve by subtracting the contribution of hole trapping estimated at a stress time of ~1 s. While the R-D model had no difficulty describing the stress data, major issues had existed for the recovery data. First pointed out by Reisinger *et al.* (25) simulation based on the R-D model showed that recovery, accounting for ~90 % of the overall, began several milliseconds after the termination of stress and lasted only for two to three orders of time interval. This behavior is in sharp contrast to the experimentally observed ultrafast recovery which begins almost instantaneously after stress and exhibits a logarithmic time dependence lasting close to ten orders of time interval (Fig. 3, 25). Grassler *et al.* (26) proposed that the discrepancy between experiment and theory may be reconciled using a dispersive proton transport

model. A dispersive transport model was also able to describe the temperature dependent time exponent observed by some authors (27), (28). As it was possible to reconcile the discrepancy between experiment and theory, most studies before 2009 supported the hydrogen transport mechanism.

It should, however, be pointed out that nearly all studies on the R-D model or its variants¹ had focused either only on the stress regime or a limited number of stress/relaxation cycles. Almost no attention was paid to the self-limiting recovery inherent in the hydrogen transport model, although this feature was already manifested in simulation results presented in earlier studies. For instance, it was shown by Krishnan *et al.* (29) that the concentration of hydrogen near the interface decreased steadily with the number of stress/relaxation cycles. This implies that recovery via the repassivation of dangling Si bonds would decrease correspondingly. The physics of self-limiting recovery is illustrated schematically in Fig. 1 (13). Following the initial recovery involving hydrogen present exactly at the interface, longer term recovery is driven by a second diffusion front created by the depletion of near-interface hydrogen during the initial stage of recovery. However, the original diffusion front which drives hydrogen away from the interface, so that interface traps may be successfully generated during stressing, still exists. Thus, even during recovery, some hydrogen is being driven away from the interface. When the transistor is stressed and relaxed numerous times, the recovery per relaxation cycle would decrease steadily (Fig. 2(a); filled circle) (8), (10), (13) since the amount of hydrogen that could move back to the interface within a given relaxation interval is gradually reducing.

Figure 1. Schematic illustration of the evolution of hydrogen concentration profile in the gate and the associated Si/SiO_2 interface state density N_{it} variation in a dynamic NBTI cycle. (a) The stress time t_s is fixed while the relaxation time t_r is varied ($t_{r2} > t_{r1}$); (b) The relaxation time t_r is fixed while the stress time t_s is varied ($t_{s2} > t_{s1}$). In either case, the hydrogen profile continues to move away from the Si/SiO_2 interface during relaxation (13).

¹ For simplicity, subsequent usage of the term “R-D model” is assumed to encompass its variants.

Figure 2. (a) Comparison of the threshold voltage V_t shift recovery per cycle or R (see left panel) measured experimentally with that obtained from R-D model simulation (8), (10), (13). (b) Variation in the magnitude of ΔV_t of a 1.7 nm EOT SiON gate p-MOSFET subjected to repeated stressing/relaxation.

On the other hand, the V_t shift recovery per cycle measured experimentally exhibits a totally different trend (Fig. 2(a); open circle). No decrease is observed after as many as 30 stress/relaxation cycles, corresponding to a cumulative time of 6×10^4 s. The difference between the V_t recovery of the last cycle and that of the first cycle is comparable to the resolution limit of V_t measurement (~ 1 mV). The constant V_t recovery is in sharp contrast to the progressive decrease predicted by the R-D model (Fig. 2(a)). Since self-limited recovery is a fundamental property of a transport model, reconciliation with the constant recovery observed experimentally is deemed not possible. The discrepancy raises a big question on the validity of the R-D model for NBTI.

It is important to emphasize that the self-limiting recovery would not show up clearly if only one or a few relaxation cycles are simulated. Despite a relatively long cumulative time of 4×10^3 s (i.e. at the end of the second dynamic cycle), the simulated recovery of the second cycle is only marginally reduced ($\sim 7\%$) as compared to the first cycle (Fig. 2(a)). This implies that self-limiting recovery is also not obvious for any simulation study that involves numerous but short stress and relaxation intervals. It should further be mentioned that the extent of self-limiting recovery may be suppressed (i.e. the gradual decrease of recovery diminished) by the use of a much higher hydrogen diffusivity during relaxation (than that during stress) such that most of the hydrogen could return to the interface. But such an attempt is not physical.

It is interesting to note the highly similar recovery curves from the first to the last relaxation cycles (Fig 3(a)) (12), (13). The fluctuation of V_t shift can also be observed to become cyclical after the initial few stress/relaxation cycles, i.e. the stress induced V_t shift is almost equal to the V_t shift recovery in each cycle (Fig. 3(b)) (10), (12), (13). In conjunction with the constant recovery per cycle (Fig. 2(a)), these results imply that it is the capture and emission of holes by the same group of pre-existing oxide defects (and not hydrogen transport) that give rise to the repetitive V_t fluctuations observed under dynamic NBTI. Studies on small area p-MOSFETs have also revealed step-like V_t recovery characterized by consistent step heights and time constants, believed to be due to the emission of holes from individual oxide traps charged by a prior stress (9), (11)².

² Some studies (30), (31) have modeled the spread in the time of step-like V_t recovery in the small area p-MOSFET in terms of stochastic transport of hydrogen back to the oxide/Si interface. The approach is

Figure 3. (a) Line: Evolution of V_t shift during individual stress and relaxation phases. For the former, data for the 10th to 30th cycles are shown. As for the latter, data for the 1st to 30th cycles are shown. The symbols denote the average value. Although the time-dependent drifts are different during stress and relaxation, the end points coincide, indicating that the total V_t shifts are nearly always equal (see left panel). The highly similar drift curves of individual stress and relaxation phases are observed regardless of the gate relaxation voltage (only the average value is shown for the case of a positive gate relaxation voltage). (b) Comparison of the total V_t shift for the individual stress and relaxation phases. The initial difference (< 5 cycles) may be ascribed to non-negligible interface state generation, which is relatively permanent. But this degradation mechanism slows down considerably between successive cycles in the later stage (see evolution of V_t shift which did not recover at the end of each relaxation phase; square), giving a clear manifestation of the cyclical V_t shift behavior (10), (12), (13).

Uncorrelated Interface and Bulk Trap Generation

The similarity between NBTI and TDDB (time-dependent dielectric breakdown) stresses (except for the magnitude of the oxide field) and the apparent success of the R-D model prior to 2009 had prompted some authors (23), (24) to ascribe the bulk trap generation observed under NBTI stressing to the interaction between the oxide network and hydrogen released from the interface state generation (Si-H bond dissociation) process. The proposed relationship between bulk and interface trap generation appeared consistent with the long standing hypothesis on oxide trap generation under TDDB stressing – the anode hydrogen release (AHR) mechanism³.

In this section, we summarize recent experimental results which show, on the contrary, no apparent relationship between interface and bulk trap generation under NBTI stressing (19). Specifically, evidence showing almost no bulk trap generation in spite of significant interface degradation under NBTI stressing will be presented. A possible explanation for the discrepancy with earlier works is given.

similar to the dispersive transport model proposed earlier and recovery should likewise be self-limited. But repeating the stress/ relaxation sequence hundreds of times on a given p-MOSFET has yielded consistent recovery step heights and time constants for individual defects (9), (11), which fail to support the inherent self-limited recovery of a transport model.

³ Under the AHR model, the dissociation of the Si-H bonds is believed to be caused by hot electrons which arise from the gate tunneling current.

Figure 4. (a) Comparison of gate leakage current before and after 40 DNBTI cycles; (b) V_t shift recovery per cycle as a function of the number of DNBTI cycles. The larger recovery under a positive gate relaxation voltage V_g^r is a result of the detrapping of deep-level trapped holes (19).

Figure 5. Evolution of $|\Delta V_t|^{\text{eos}}$ and $|\Delta V_t|^{\text{eor}}$, the respective V_t shift at the end of the stress and relaxation phase, of an ultrathin SiON (EOT = 1.7 nm) gate p-MOSFET subjected to repetitive stress/relaxation cycling. $|\Delta V_t|^{\text{eos}}$ measures the total positive trapped charge in the gate oxide prior to the onset of relaxation while $|\Delta V_t|^{\text{eor}}$ gives the part of the V_t shift which did not recover at the end of each relaxation phase (19).

In Fig. 4(a), the gate tunneling current I_g of an ultrathin oxynitride gate p-MOSFET (equivalent oxide thickness, EOT = 1.7 nm) before and after 40 stress/relaxation cycles are compared. No increase of I_g can be observed, which implies no generation of bulk traps despite a cumulative stress time of 4×10^4 s⁴. This result is in agreement with the constant V_t recovery (Fig. 4(b)), confirming that there is no observable increase of oxide trap density and the V_t fluctuations under gate pulsing arise from hole trapping/detrapping at pre-existing oxide traps, as concluded previously.

⁴ A separate study involving p-MOSFETs with a thicker SiO₂ gate oxide (2.8 nm) and pre-stress I_g on the order of 10^{-12} A at 1 V also showed no increase of I_g after 5×10^4 s of NBTI stressing at comparable oxide field [Fig. 7, 19]. This rules out the possibility that any increase of I_g in Fig. 5 is masked out by the relatively high pre-stress I_g of the thinner oxynitride gate oxide.

On the other hand, a steady rise of the remnant V_t shift (i.e. the relatively permanent part of V_t shift which did not recover) at the end of each relaxation phase is evident (Fig. 5), reaching ~ 30 mV at the end of the 40th stress/relaxation cycle. It should be mentioned that part of the remnant V_t shift obtained under 0 V gate recovery voltage is due to holes trapped at pre-existing deep-level oxide traps (32), (33). The results in Fig. 7 are obtained under a +1 V gate recovery voltage, under which the contribution from deep-level trapped holes has been excluded (cf. Fig. 4(b) which shows a larger V_t shift recovery, due to increased hole detrapping, under +1 V as compared to 0 V gate recovery voltage). Since no bulk trap generation is observed, the non-negligible remnant V_t shift must be due to defects located at or very near the oxide/Si interface. The remnant V_t shift of 30 mV corresponds to a sizeable interface state density of $4 \times 10^{11} \text{ cm}^{-2}$, indicating that significant interface state generation has occurred under the stress condition applied. The results show clearly that the substantial interface degradation induced by NBTI stressing did not result in any apparent bulk trap generation.

It is therefore essential to address the apparent discrepancy between this set of results, which show no bulk trap generation in spite of significant interface degradation, and the earlier observation of bulk trap generation under NBTI stressing (23), (24). It should be noted that there has been no explicit evidence confirming that the bulk trap generation observed in earlier studies stemmed from hydrogen released from the interface degradation process. The inference was drawn based on the correlated increase of stress induced leakage current (SILC) and charge pumping current (I_{cp}) (23) or subthreshold swing (SS) (24), on the *presumption* that the interface defects sensed by the I_{cp} or SS are dangling Si bonds or P_b centers that result from Si-H bond dissociation. While the P_b center is a major source of defects at the SiO₂/Si interface, it may not be the case for the more advanced gate oxide which incorporates a non-negligible amount of nitrogen and fluorine (from BF₂ implantation). The latter has been shown to lessen the NBTI effect (3) and it is believed that this occurs through the formation of stronger Si-F bonds in place of the Si-H bonds. Electron-spin resonance study (34) of a post-stressed plasma-nitrided gate p-MOSFET has also not found any signal related to the P_b center but a totally different and dominant signal related to a near-interface oxygen vacancy defect (the k_N center). The evidence implies that the NBTI of modern p-MOSFETs may be dominated by defects other than the P_b center.

It should be mentioned that a near-interface oxygen vacancy defect could effectively function as an interface trap during electrical measurement and be sensed by techniques such as the charge pumping and subthreshold swing. At the same time, these defects could function as trap-assisted tunneling centers, i.e. oxide traps that result in a higher gate leakage current. As will be shown in the next section, it is possible for oxide traps to be generated under certain NBTI stress condition⁵ that give rise to an apparent relationship between SILC and interface state generation, especially in the ultra-thin gate p-MOSFET (23), (24).

Transient to Permanent Trapped-Hole Transformation

As discussed in the second section, the recovery of V_t shift per cycle is constant independent of the number of times the device is stressed and relaxed. This evidence

⁵ The extent of oxide defect generation depends on the processing conditions and may vary substantially from one case to another for a given stress condition.

Figure 6. (a) Evolution of $|\Delta V_t|^{eos}$ and $|\Delta V_t|^{eor}$ of two similar p-MOSFETs but subjected to different test patterns. In one case (DNBTI), only repeated NBTI stress/relaxation cycling was applied. The gate stress voltage was -1.8 V and the gate relaxation voltage was 0 V. The stress and relaxation phase each lasted 1×10^3 s. In the other case (DNBTI-CVS), a constant voltage stressing phase follows the DNBTI test. The CVS was carried out at a much higher gate stress voltage of 3 V but only for a short interval of 50 s. The DNBTI test was repeated after the CVS phase and the sequence repeated. (b) Comparison of the V_t shift recovery per cycle under the DNBTI and DNBTI-CVS test sequences (18).

strongly suggests that the observed V_t shift fluctuation is a result of the capture and emission of holes by a similar group of pre-existing oxide defects that always respond under a given experimental condition. As will be shown in this section, a gradual decrease of the V_t shift recovery per cycle can be observed, especially under high oxide stress field and temperature (14), (16), (18), (20)-(22). We present evidence which shows that the decrease is a result of a part of the transient (recoverable) trapped holes being transformed into more permanent ones. The linear correlation between the decrease of V_t recovery and SILC lends support to our hypothesis that the transformation is a key mechanism for the permanent bulk trap generation observed by some early studies (23), (24).

In Fig. 6(a) (18), the V_t shift at the end of the stress and relaxation phases, $|\Delta V_t|^{eos}$ and $|\Delta V_t|^{eor}$, respectively, of two similar devices subjected to numerous dynamic gate cycles, are plotted. In one case, the usual dynamic NBTI test was repetitively applied, such as in the case of Fig. 2. In the second case, an intermediate constant voltage stressing (CVS) phase was inserted in-between two successive dynamic NBTI cycles. For instance, upon the completion of the first dynamic NBTI cycle, the device was subjected to CVS, at a much higher oxide stress field than that applied during the NBTI stress. The dynamic NBTI test was resumed after the CVS and the DNBTI-CVS sequence was repeated numerous times. As can be seen from Fig. 6(b) (18), the V_t recovery per cycle decreases with the number of times the DNBTI-CVS sequence was repeated, in contrast to the case where the CVS phase was omitted.

An explanation for the decrease of V_t recovery per cycle under repeated DNBTI-CVS testing may be found in Fig. 6(a), in which the evolution of $|\Delta V_t|^{eos}$ and $|\Delta V_t|^{eor}$ are compared to those of the case where the CVS phase was excluded. It should be mentioned that $|\Delta V_t|^{eos}$ measures the total positive trapped charge (trapped holes and interface trapped charge) in the gate oxide whereas $|\Delta V_t|^{eor}$ probes the fraction of positive trapped charge remaining after each relaxation phase, i.e. the part which is relatively permanent and did not recover. Apart from the initially larger $|\Delta V_t|^{eos}$ for the DNBTI-CVS test, it can be seen

Figure 7. (a) Evolution of V_t shift recovery per cycle under different temperatures. The gate stress voltages are as indicated. (b) Evolution of $|\Delta V_t|^{\text{eos}}$ and $|\Delta V_t|^{\text{eor}}$ at 100 °C and 220 °C, with the gate stress voltage fixed at -1.8 V (22).

that the subsequent evolution of $|\Delta V_t|^{\text{eos}}$ is comparable to that of the DNBTI-only (i.e. CVS excluded) test. This implies that the incremental total positive trapped charge in both cases are rising at similar rates, i.e. there is no substantial additional positive charge generation except in the initial stage of the DNBTI-CVS test. On the other hand, the $|\Delta V_t|^{\text{eor}}$ of the DNBTI-CVS test increases more rapidly as compared to that of the DNBTI-only test. This implies that the portion of relatively permanent positive trapped charge is increasing at a faster rate in the former. Since the total positive trapped charge is increasing at comparable rates, the results therefore indicate that in the case of the DNBTI-CVS test, the CVS phase has gradually transformed a part of the recoverable trapped holes into a more permanent form.

A similar observation is obtained when the temperature of the DNBTI test is increased, as shown in Fig. 7 (22). In this case, no intermediate CVS was performed and the DNBTI conditions for the two cases were the same except for the temperature. One experiment was performed at 220 °C and the other at 100 °C. For the former, the V_t recovery per cycle gradually decreases while that of the latter remains constant (as in Fig. 2). Fig. 7(b) shows that the reduction in the V_t recovery per cycle stems from the transformation of a portion of the recoverable (or transient) hole trapping into more permanent form.

In another set of experiments, gate current measurement was also made at the end of the relaxation interval to examine the impact of such transformation on the gate oxide integrity and the results are shown in Fig. 8 (22). Almost no SILC can be observed when the V_t recovery per cycle remains constant (as in Fig. 4). However, whenever a decrease of the V_t recovery per cycle is observed, SILC generation is also observed – the two are found to exhibit a very good linear correlation as shown in Fig. 9. Similar observations apply to the case of DNBTI-CVS testing depicted in Fig. 6. As the increase of SILC implies the generation of bulk traps, the linear correlation leads us to conclude that the bulk traps originate from the transient-to-permanent transformation of hole trapping. We believe such transformation (and not Si-H bond dissociation) underlies the observation of bulk trap generation reported in earlier studies (23), (24). It should be emphasized that similar results are obtained for high-k gate p-MOSFETs (14), (16), (20), (21) implying the observed phenomenon is generic across different gate oxide materials.

Figure 8. Gate current I_g versus gate voltage V_g for different DNBTI conditions (A, B and C correspond to the conditions stated in Fig. 7) (22).

Figure 9. (a)(i) At a high temperature (220 °C), the decrease in the V_t shift recovery per cycle is seen to track the increase of stress induced leakage current very closely. (a)(ii) An excellent linear correlation can be observed between the two. (b)(i) and (b)(ii) Similar results holds for the DNBTI-CVS testing described earlier (18), (22).

Before concluding, we would like to provide a plausible explanation for the observed hole trapping transformation, based upon the current understanding on the nature of hole traps in the traditional SiO_2 and SiON gate dielectrics as well as the high-k gate

dielectrics. Oxygen vacancies V_O 's are a major source of hole traps in these gate dielectrics. Upon the capture of a hole, rearrangement of the atoms around the defect occurs to accommodate the loss of an electronic charge. We expect such structural relaxation to entail the overcoming of a certain energy barrier determined by the local oxide chemistry. If such a barrier is not overcome, permanent structural change could not occur and the hole trapping is temporary, i.e. the trapped hole is readily re-emitted when the electrical stressing is removed. For instance, *ab-initio* simulation has revealed a category of V_O 's, called the E_δ' center, in the SiO_2 (35), (36). Upon the capture of a hole, structural relaxation of the Si–Si dimer of the E_δ' center is marginal (in fact the remaining electron is shared between the two Si atoms). The positively charged, singly bonded Si–Si dimer reverts to the neutral, doubly bonded Si=Si dimer immediately upon the reintroduction of an electronic charge to the defect site. On the other hand, there also exists a group of V_O 's called the E_γ' centers for which a substantially greater structural relaxation occurs upon the capture of a hole. The energy barrier for structural relaxation to occur in the E_γ' center is presumably smaller than that for the E_δ' . Indeed, examination of the local bonding network has revealed that the E_γ' center is usually found in places where a void exists to allow one of the Si atoms to move and become back-bonded to a nearby oxygen atom to reach an energetically favorable state. One expects the energy barrier to be more easily overcome under a high oxide field and temperature, which introduce greater distortion to the oxide network.

Similar *ab-initio* simulation study on the SiON (37) and HfO_2 has been made by our group and results show that a larger percentage of the V_O 's in these gate dielectrics exhibit substantial structural relaxation following the capture of holes as compared to the SiO_2 . For the SiON , it was found that a neighboring nitrogen atom could facilitate the structural relaxation of V_O through N–Si bond formation involving the former's lone pair (a mechanism we believe to be similar to the back bonding of Si to a nearby O atom in the case of the E_γ' center. As for the HfO_2 , we attribute the result to its greater ionicity and the stronger electron-lattice interaction. These simulation results may explain 1) why V_O 's in the plasma-nitrided gate oxide following NBTI stressing could be observed using conventional electron-spin resonance (ESR) method (34) whereas the same method applied on the SiO_2 yielded a negative result. Recently, V_O 's were successfully observed in the SiO_2 with ESR measurement carried out on-the-fly (i.e. with the stress continuously applied) (38). 2) The oxide field and temperature thresholds for SILC or bulk trap generation and for the decrease of the V_t recovery per cycle in the HfO_2 gate p-MOSFET are much lower than those for the SiO_2 gate devices (14), (16), (20), (21).

Summary

An overview of recent key experimental evidences highlighting the importance of hole trapping in NBTI is presented. The role of hole trapping was unappreciated (and in fact regarded as a parasitic effect) when the focus was largely on the R-D model in the past. But as revealed in recent studies on DNBTI, the transport model is unable to explain the cyclical fluctuation and constant recovery of the V_t shift. These observations are better described in terms of hole trapping/detrapping at a group of pre-existing oxide traps which consistently respond under a given set of experimental conditions. Moreover, experimental evidence which challenges a previous hypothesis that oxide trap generation is driven by hydrogen released from the dissociation of Si–H bonds (at the interface) is presented. In particular, no apparent bulk trap generation is observed in spite of significant

interface degradation. Instead, bulk trap generation is observed to correspond to the reduction of V_t recovery or transient hole trapping, implying that the former stems from the transformation of transient to permanent hole trapping.

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