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Impact of Lanthanum on Positive-Bias Temperature Instability – Insight from First-Principles Simulation

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The impact of lanthanum (La) on positive-bias temperature instability (PBTI) is examined via first-principles simulation of the electronic properties of the oxygen vacancy (V_O) and vacancy-interstitial (V_O - O_i) paired defects in the hafnium dioxide (HfO_2) gate dielectric. The purpose is to understand the recently reported retardation of PBTI recovery in La-doped HfO_2 gate n-MOSFETs, indicating that La doping has made part of the stress induced electron trapping become more permanent. Simulation results show that the formation energy of both defects are significantly decreased by La doping, implying that these defects are more readily formed in the La-doped HfO_2 as compared to the undoped counterpart. The higher density of V_O 's should increase PBTI effect, contrary to the experimental observation of a reduced PBTI effect. The discrepancy may be reconciled by the smaller gate current in the La-doped n-MOSFET, believed to be due to the larger tunneling barrier that results from La dipoles at the HfO_2/SiO_x interface. With a smaller gate current, electron trapping – the main mechanism of PBTI – is correspondingly reduced. But the trap state of V_O in the La-doped HfO_2 remains as shallow as that in the undoped counterpart and could not account for the reduction in the PBTI recovery observed experimentally. On the other hand, the trap state of the V_O - O_i defect is found to be much deeper, and the greater ease of its formation in the La-doped HfO_2 could explain the reduced PBTI recovery observed experimentally.

Introduction

It is now recognized that the traditional silicon oxynitride (SiON) gate dielectric has to make way for high-permittivity or high-k metal oxides in sub-32 nm complementary metal-oxide-semiconductor (CMOS) technologies. The main reason is that the aggressive scaling down of the SiON thickness has led to an unacceptably high gate leakage current density. This problem could only be resolved by the use of a physically thicker high-k oxide to keep the gate tunneling current in check while maintaining the desired gate capacitance that helps prevent the loss of performance. Among the many high-k oxides studied in the past decade, the hafnium dioxide or HfO_2 has emerged as one of the most suitable candidates and has already been adopted in recent commercial CMOS technologies.

However, there are still several difficult issues surrounding high-k oxide integration. One of the major challenges is the difficulty in realizing transistors with low threshold

voltages or V_t 's. For instance, the V_t of a polysilicon/HfO₂ gate n-channel transistor was ~ 0.7 V. Fermi level pinning at the polysilicon interface was shown to be one of the main reasons for the high V_t (1). Although the use of metal gates had helped alleviate the problem, the V_t of HfO₂/TiN gate transistors remained high (~ 0.4 V). Recent studies (2) found that dipoles at the HfO₂/SiO_x interface also played a major role in the high V_t obtained and the result was successfully explained by a model proposed by Kita and Toriumi (3). According to this model, the intrinsically higher oxygen areal density of HfO₂ results in the formation of dipoles (positive end on the HfO₂ side) via the transfer of oxygen ions (O^{2-}) to the underlying SiO_x. As a consequence, the flat band voltage is shifted positively. The model also predicts that some rare-earth oxides such as La₂O₃, which have lower oxygen areal densities, would form dipoles of opposite orientation at the SiO_x interface. Several experimental studies (2, 4, 5) have exploited this effect to successfully reduce the V_t of n-channel transistors.

But the incorporation of lanthanum or La has raised a concern on gate stack reliability. To-date, mixed observations have been made. For instance, La doping of the HfO₂ was shown to reduce the positive-bias temperature instability or PBTI effect of the n-channel metal-oxide-semiconductor field-effect transistor (n-MOSFET) at a low oxide stress field (6, 7). However, the PBTI effect was worse under a high oxide stress field. Time-dependent dielectric breakdown or TDDB test revealed a similar observation where it was found that degradation of the La-doped HfO₂ scaled more quickly with oxide stress field as compared to that of the undoped HfO₂ (6). It was recently found that PBTI recovery of a La-doped HfSiO gate n-MOSFET proceeded at a much slower pace as compared to that of an undoped counterpart, indicating that La doping made the PBTI effect more permanent. To-date, however, it remains unclear why La doping has different impacts in the low and high oxide field regimes and why it retards PBTI recovery. In this paper, we attempt to provide a plausible explanation via a first-principles simulation study of the effect of La on the electronic properties of the oxygen vacancy (V_O) defect as well as the related vacancy-interstitial (V_O -O_i) paired defect in the HfO₂.

La-Induced Slowing Down of PBTI Recovery

Before describing the simulation method and results, we first present a review of recent experimental results which show that La slows down PBTI recovery (8). The n-MOSFET studied had a TiN/HfSiO/SiON gate stack (of 1.6 nm equivalent oxide thickness) processed under a gate-first flow. La doping was realized by a thin LaO_x cap layer, atomic-layer deposited and subsequently diffused into the HfSiO via the high temperature source/drain annealing step. To ascertain that the observed slow-down of PBTI recovery was not due to a specific process, comparison was made to a variety of other devices: 1) undoped p-MOSFETs on the same wafer as the La-doped n-MOSFET; 2) n-MOSFETs with undoped 3-nm HfO₂ and 2-nm HfSiON grown via metal-organic chemical vapor deposition over a 1-nm chemical oxide (the gate electrode was polysilicon and TaN, respectively); 3) n- and p-MOSFETs with undoped HfO₂(3 nm)/SiO_x(0.9 nm) gate stacks; 4) p-MOSFETs with the traditional polysilicon gate and SiON gate dielectric

Figure 1. (a) Linear drain current degradation ΔI_d (in percent), measured at two different delays, of a La-doped n-MOSFET and undoped p-MOSFET (on the same wafer) as a function of stress time. (b) Typical logarithmic time dependence of ΔI_d recovery (expressed as a percentage of the total I_d degradation at the end of stress) of a variety of n- and p-MOSFETs with different gate stacks, subjected to PBTI and NBTI stress, respectively. The number in the bracket refers to the dielectric thickness (8).

(1.8 and 2.2 nm). The n- and p-MOSFETs were subjected to positive-bias and negative-bias temperature stressing, respectively.

The observation that has led us to the finding of La induced slow-down in PBTI recovery is shown in Fig. 1(a) (8). Stress induced linear drain current degradation ΔI_d (in percent) of the La-doped n-MOSFET and undoped p-MOSFET (on the same wafer), are compared at different measurement delays¹ (8). When the delay is short ($1 \mu\text{s}$), the ΔI_d of the p-MOSFET is greater than that of the n-MOSFET. At a much longer delay (1 s), however, a reversal is observed. Both PBTI and NBTI are known to recover upon the termination of electrical stress and a longer delay means a greater recovery would have occurred before the I_d measurement is made. The reversal observed implies that the degraded La-doped n-MOSFET and undoped p-MOSFET are recovering at very different rates. Fig. 1(b) confirms that it is the La-doped n-MOSFET which has an abnormally slow recovery. As shown, the recovery of the undoped p-MOSFET is comparable to a variety of other devices with different gate dielectrics and gate electrodes. On the other hand, the La-doped n-MOSFET exhibits a substantially slower recovery as compared to the rest of the undoped devices.

Studies have shown that electron and hole trapping (at oxide defects), respectively, is responsible in part for the PBTI and NBTI (9) effect. Recovery due to electron or hole detrapping typically spans a broad range of timing, from as short as microseconds (limited by the measurement speed of the instrument) to beyond 10^6 s (10, 11). The classical tunneling-front model (12), which ascribes the dispersion in the recovery times to the emission of filled traps situated at varying distances from the oxide interface, could not explain such a broad range of recovery time (spanning more than 10 orders of magnitude) measured on

¹ Time lapse between the termination of electrical stress and the start of drain current measurement

Figure 2. (a) Schematic energy band diagram for the TiN/HfO₂/Si structure showing (i) a detrapping barrier ϕ of a deep electron trap under $V_g = 0$ and (ii) reduction of the barrier by a negative gate bias, which facilitates emission of the trapped electron. (b) Schematic depiction of a deep hole trap, where emission of the trapped hole (via the capture of an electron from the Si substrate) is hindered by the barrier ϕ . Under a positive gate bias, the hole trap is lowered below the Si conduction band and is neutralized by an injecting electron.

Figure 3. (a) Evolution of threshold voltage shift ΔV_t during a cycle of PBTI stress and relaxation of an undoped HfO₂/TiN gate n-MOSFET. ΔV_t is expressed as a percentage of the total ΔV_t at the end of the stress phase. (b) Recovery of linear drain current degradation ΔI_d , expressed as a percentage of the total degradation at the end of stressing, for the La-doped n-MOSFET and undoped p-MOSFET under different gate relaxation voltages (8).

very thin gate stacks (~ 3 nm or less in thickness). The result implies that some of the charges are captured by deep oxide traps, whose emission time constants are primarily controlled by the potential barrier that exists between the trap state and the conduction band of the Si substrate (as illustrated schematically in Fig. 2) and not by the distance of the trap from the oxide interface. This inference is supported by the dependence of

Figure 4. Recovery of oxide defects at and near the SiO_x/Si interface (as probed by the charge pumping method at 1 MHz) of the La-doped n-MOSFET and undoped p-MOSFET following PBTI and NBTI stressing, respectively. ΔI_{cp} is expressed as a percentage of the total ΔI_{cp} at the end of stress (8).

degradation recovery on the gate voltage V_g (Fig. 3). As shown in Fig. 3(a) for the case of PBTI, the V_t shift recovery under $V_g = 0$ V is seen to hit a “plateau” soon after the initial steep reduction, indicating that electron detrapping has slowed down substantially. However, a switch in V_g to -1 V can be seen to trigger another abrupt V_t shift reduction. This rapid second V_t shift recovery may be explained by a lowering of the electron detrapping barrier, as a result of the “rise” in the trap state brought about by the negative V_g (Fig. 2(a)(ii)). A similar dependence of NBTI recovery on V_g can be seen in Fig. 3(b). On the other hand, recovery of the La-doped n-MOSFET exhibits a much weaker dependence on V_g . Only a marginal reduction in ΔI_d (relative to the overall degradation) is observed at the various instants of V_g change, as compared to that of the undoped HfO_2 . This result suggests that the slow-down in PBTI recovery is due to a higher density of deep-level electron traps in the La-doped gate stack.

Results from high-frequency (1 MHz) charge pumping current (I_{cp}) measurement (Fig. 4), which probes defects close to the oxide/Si interface, imply that the deep-level electron traps responsible for the slow-down in PBTI recovery are mostly contained in the high-k oxide. As can be seen from the recovery characteristics, the percentage recovery of ΔI_{cp} for the La-doped n-MOSFET is actually larger than that for the undoped p-MOSFET. This result cannot explain the much smaller percentage recovery of ΔI_d for the former. Thus, it is inferred that the observed slow-down of PBTI recovery is mostly a bulk effect, in agreement with previous studies (13) asserting that oxide trapping dominates PBTI. As will be shown below, La's presence lowers the formation energy of the $\text{V}_\text{O}-\text{O}_\text{i}$ paired defect, which can function as a deep-level electron trap in the HfO_2 .

First-Principles Simulation

To provide a theoretical support for the above conclusion drawn from the electrical measurement results, *ab-initio* simulation study on the electronic properties of defects in

Figure 5. (a) Ball and stick diagram of part of the defect-free HfO_2 supercell used in our simulation study. (b) Two Hf atoms are replaced by La atoms to simulate La doping of the HfO_2 . (c) The O atom in between the two Hf atoms was manually removed to create an oxygen vacancy (V_{O}) defect. (d) The V_{O} defect is formed in between two La atoms in the La doped HfO_2 .

the La-doped and undoped HfO_2 was carried out. The supercell used is amorphous HfO_2 , comprising 32 Hf atoms and 64 O atoms, with a density of 9.68 g/cm^3 . The dimensions of the supercell are $10.23 \text{ \AA} \times 10.23 \text{ \AA} \times 10.23 \text{ \AA}$. The amorphous structure was generated from a cubic HfO_2 structure, via molecular dynamics, following the melt-and-quench scheme (14). The cubic HfO_2 structure was “heated” to a temperature of 2500 K and maintained at that temperature for 3 ps to fully liquefy the system. The temperature was then lowered to 300 K in 1 ps. This was followed by a 3-ps period at 300 K to achieve the thermal equilibrium structure. Finally, structural relaxation of atomic coordinates was carried out at 0 K. Fig. 5(a) is a ball and stick diagram of part of the defect-free HfO_2 supercell. La doping was realized by manually replacing two nearby Hf atoms with La atoms and then allowing the system to relax again to the minimum energy state (Fig. 5(b)).

All calculations were performed using VASP (15), which employs the plane wave pseudo-potential methods within the density functional theory. A hybrid density functional scheme was applied to obtain the correct HfO_2 band gap (16). The ultra-soft pseudo-potentials were used to represent the interactions between the ion core and the valence electrons (17). The exchange correlation functional was treated within the GGA of Perdew Burke and Ernzerhof (18). In all calculations, the cut-off energy and Γ -point were tested. For structure optimization, the conjugate gradient method was used and the ion positions were optimized until the residual force was less than $0.01 \text{ eV/\AA}$.

Figure 6. Schematic energy band diagram illustrating the charge transition level (akin to the trap level) of the oxygen vacancy (V_O) and vacancy-interstitial (V_O - O_i) defect in the (a) undoped HfO_2 and (b) La-doped HfO_2 .

Oxygen Vacancy Defect

The first part of the simulation study was focused on V_O , a major source of defects in the high-k oxide. Charge trapping at V_O 's is generally believed to be responsible for the V_t instability observed experimentally (19). The impact of La is examined by comparing the formation energy E_f of V_O in the La-doped and undoped HfO_2 . The E_f of a defect may be obtained from the difference in the total energy E of the defective and defect-free supercell according to:

$$E_f(\alpha, q) = E(\alpha, q) - (E_0^0 + n_{Hf}\mu_{Hf} + n_O\mu_O + n_{La}\mu_{La}) + q(\varepsilon_F + E_{VBM}) \quad [1]$$

where E_0^0 is system energy of the defect-free supercell and E_{VBM} is the valence band maximum of HfO_2 . For a defect α in charge state q , E_f is a function of the Fermi level ε_F and the respective chemical potential of Hf, O and La, denoted by μ_{Hf} , μ_O , and μ_{La} , respectively. The terms n_{Hf} , n_O and n_{La} represent the corresponding number of Hf, O and La atom(s) added/removed from the supercell to form the defect.

In the undoped HfO_2 , a V_O defect was formed by manually removing the O atom between two Hf atoms (Fig. 5(c)). The same method was used to form a V_O defect in the La-doped HfO_2 by removing the O atom between two La atoms (Fig. 5(d)). The oxygen-deficient supercell in each case was then relaxed until the minimum energy state was attained. Using this method, the E_f for the V_O defect in the undoped and La-doped HfO_2 are determined as 5.85 eV and -3.78 eV, respectively. Clearly, the presence of La has a significant impact on V_O formation in the HfO_2 . The substantially reduced E_f (negative in fact) implies that La doping increases the likelihood of V_O defect formation in the HfO_2 .

Besides E_f , the charge transition level or CTL for neutral-to-negative state transition of the V_O defect was also calculated to examine its role on electron trapping under PBTI stress. The CTL is defined as the Fermi energy ε_F that corresponds to $E_f(\alpha, q) = 0$ for both the neutral and negative charged V_O defect. The 0/- CTL measured with respect to E_{VBM} of the

Figure 7. (a) Ball and stick representation of the amorphous HfO_2 supercell with a $V_{\text{O}}\text{-O}_{\text{i}}$ defect, created by removing one of the O atoms in between two Hf atoms (see labels) and placing it randomly in an interstitial position (O_{i}) close to the V_{O} defect. (b) A similar representation of the $V_{\text{O}}\text{-O}_{\text{i}}$ defect in the La-doped HfO_2 supercell. In this case, the O_{i} was originally located in between the two La atoms.

HfO_2 is akin to the electron trap level of the V_{O} defect in the HfO_2 bandgap (16). The 0/-CTL of the V_{O} defect in the undoped HfO_2 (Fig. 5(d)) is determined as 4.75 eV. The results are in agreement with previous studies (20, 21), indicating that V_{O} 's in the HfO_2 function give rise to shallow electron traps. It should be mentioned that our calculation did not involve only a single V_{O} defect but all 64 possible cases in the amorphous supercell (comprising 64 O atoms). No difference (statistically) in the CTL for the La-doped and undoped HfO_2 can be observed; the average CTL is ~ 4.7 eV with a spread of ~ 0.3 eV for both cases. Thus, La doping has no apparent impact on the trap energy level. Schematic energy band diagrams showing the positions of the V_{O} CTL in the undoped and La-doped HfO_2 are given Fig. 6.

Formation of the V_{O} defect in the La-doped HfO_2 was also studied via first-principles simulation by Umezawa *et al.* (22) and Liu and Robertson (23). However, these studies reported an increase in E_{f} (by ~ 0.7 eV), contrary to the significant reduction obtained in our case. We believe the discrepancy is due to the different ways by which the V_{O} defect is generated. In Umezawa *et al.*, the authors removed altogether two O atoms when creating a V_{O} defect in the La-doped HfO_2 . In replacing two Hf atoms by La atoms to simulate La doping, one O atom was also removed to avoid the formation of a hole at the La substitutional sites, due to the difference in the formal charges of La^{3+} and Hf^{4+} . This was followed by the removal of a second O atom to generate a V_{O} defect in the La-doped HfO_2 . The removal of two O atoms may explain the much higher E_{f} of 6.29 eV (more positive than that of an undoped HfO_2) obtained by the authors (22). In our case, however, such treatment is deemed not necessary by virtue of the amorphous supercell. The negative E_{f} means that our structure is energetically more favorable as compared to those considered in (22, 23).

The observation of a negative E_{f} for the V_{O} defect in the La-doped HfO_2 implies that this gate dielectric should have a higher density of V_{O} 's as compared to the undoped HfO_2 . Thus, PBTI of the La-doped HfO_2 n-MOSFET should correspondingly be degraded. This appears to contradict experimental studies which have shown that PBTI of the La-doped n-MOSFET is improved as compared to the undoped counterpart (6). The discrepancy might have prompted some authors ((22, 23)) to address the issue of charge neutrality as

elaborated above. Although the resultant higher E_f , which implies that V_O formation is suppressed in the La-doped HfO_2 , could explain the reduced PBTI effect observed experimentally, the simulation result could not explain 1) the increased susceptibility of the La-doped HfO_2 to stress induced degradation under a high oxide field; 2) the retardation of PBTI recovery given that the V_O CTL is as shallow as that of the undoped HfO_2 .

The greater ease of V_O formation in the La-doped HfO_2 , as revealed by our simulation result, may be reconciled with the experimental observation of a lesser PBTI effect at a low oxide stress field (24) by referring to a recent report on reduced gate tunneling current in the La-doped n-MOSFET biased in the positive regime (25) (26). The lower gate tunneling current is attributed to dipoles formed between La and the underlying SiO_x , which increase the barrier at the $\text{HfO}_2/\text{SiO}_x$ interface for electron injection from the n-channel (see Fig. 7 of (25)). It should be mentioned that the barrier in question is relevant only under a low positive gate voltage where electron tunneling occurs through both the SiO_x interfacial layer and the La-doped HfO_2 . At a higher positive gate voltage, electron tunneling occurs through the SiO_x only and the benefit associated with the La-dipole-induced $\text{HfO}_2/\text{SiO}_x$ barrier increase should vanish. While the above may explain the lesser PBTI effect observed under a low oxide stress field as well as the greater PBTI effect at a higher oxide stress field, the shallow trap states due to V_O fail to account for the slow-down of PBTI recovery observed in the La-doped HfO_2 .

Vacancy-Interstitial Defect

In explaining the slow-down of the PBTI recovery depicted in Figs. 1 and 3, the defect concerned should be a relatively deep electron trap. For a non-zero electron detrapping barrier (Fig. 2(a)), the trap state should be situated below the Si conduction band minimum E_{CBM} . The V_O defect in the HfO_2 fails to meet this requirement due to its rather shallow trap state. Moreover, as shown in Fig. 6, the average CTL of ~ 4.7 eV is similar for both the undoped and La-doped HfO_2 , which could not explain the slow-down in PBTI recovery observed for the La-doped HfO_2 n-MOSFET. In this section, we show that the related vacancy-interstitial ($V_O\text{-O}_i$) defect can give rise to a deep electron trap in the HfO_2 bandgap and the ease of $V_O\text{-O}_i$ generation in the La-doped HfO_2 is greatly enhanced over the undoped counterpart.

In our simulation study, the $V_O\text{-O}_i$ defect was manually created by removing the O atom in between two Hf or La atoms and placing it at an interstitial position in the vicinity of the V_O defect created. The resultant structure was then allowed to relax fully prior to the computation of E_f and CTL. Examples of the $V_O\text{-O}_i$ defect in the undoped and La-doped HfO_2 are shown in Fig. 7(a) and (b), respectively. Numerous randomly chosen O_i positions for a given V_O position were investigated for each case.

Interestingly, the CTL of the $V_O\text{-O}_i$ defect is more scattered, and could range from anywhere below the E_{VBM} of the HfO_2 to near the CTL of the V_O defect, depending on the position of the O_i atom. Some examples are shown schematically in Fig. 6. This wide spread in the trap state makes the $V_O\text{-O}_i$ defect a suitable candidate for a deep electron trap. For the undoped HfO_2 , the E_f for the $V_O\text{-O}_i$ defect is determined as 6.7 eV. On the other hand, the E_f is ~ -2.8 eV for the La doped HfO_2 . The negative E_f indicates that $V_O\text{-O}_i$ defects are also energetically more favorable, i.e. they are more easily formed in the La-doped HfO_2 as compared to the undoped HfO_2 . A higher $V_O\text{-O}_i$ defect density in the former

may explain the slow-down in the PBTI recovery observed as electrons captured at the relatively deep trap states are more difficult to be emitted in a given time interval.

Previous simulation studies (20) have shown that an interstitial oxygen atom alone can give rise to a deep electron trap with energy state near the E_{VBM} of the HfO_2 . However, the likelihood of O_i existing on its own is low since nearly all high-k oxides are deficient in oxygen. In our simulation model, the O_i atom comes from an O atom displaced from its original lattice position (in between two Hf atoms). As high-k oxides have a strong ionic character, electric-field induced atomic displacement is a likely scenario in these materials, considering the relatively high field in thin gate stacks. The CTL of the resultant V_O - O_i defect could lie anywhere in the HfO_2 bandgap depending on the position of the O_i atom. Our simulation study has shown that at certain positions of the O_i atom, the CTL is relatively shallow and electron trapping occurs mainly at the V_O site. However, at other O_i positions, electron trapping occurs mainly at the O_i site and the resultant CTL is deeper, i.e. at these positions, we may regard the O_i atom to have effectively deactivated the shallower V_O defect. This behavior may explain the electrical conductance switching of high-k oxides revealed in recent experimental studies and details will be discussed elsewhere.

Besides being able to explain the slow-down in PBTI recovery of the La-doped HfO_2 , the V_O - O_i defect model could also qualitatively account for the worse PBTI effect observed under a high oxide stress field. The negative E_f implies that the energy barrier for the generation of the V_O - O_i defect in the La-doped HfO_2 is lower than that of the undoped HfO_2 . Thus, under a given oxide field, generation of the V_O - O_i defect could occur more readily in the La-doped HfO_2 . Barrier reduction induced by the applied oxide field could further accelerate the generation of the V_O - O_i defect in the La-doped HfO_2 , leading to a much worse PBTI effect as compared to that of the undoped HfO_2 .

Summary

First-principles simulation performed on an amorphous HfO_2 structure shows that La doping could significantly reduce the E_f (becoming negative in fact) for the V_O defect, indicating that such defects are more likely to be formed in the La-doped HfO_2 as compared to the undoped counterpart. It is thus proposed that the reduced PBTI effect in the La-doped HfO_2 at a low oxide field is not because of the suppressed formation of V_O , as claimed in previous simulation studies, but may be due to the smaller gate current that results from the La induced tunneling-barrier increase at the $\text{HfO}_2/\text{SiO}_x$ interface. Results also show that La doping has no apparent impact on the 0/- CTL of the V_O defect, which remains as shallow as that in the undoped HfO_2 . Thus, the V_O defect model alone could not explain the slow-down in PBTI recovery observed experimentally. We show, however, that the 0/- CTL of a related defect, namely the V_O - O_i paired defect, could range anywhere from the E_{VBM} to the E_{CBM} of the HfO_2 , depending on the position of the interstitial O atom. Thus, at certain “strategic” positions of the O_i , this defect could function as a deep electron trap. Our choice of the V_O - O_i defect is guided by the generally strong ionic character of high-k oxides, which implies that field induced displacement of the relatively light O atoms is a likely scenario in these materials in view of the relatively high field in thin gate stacks. It is shown that the zero-field E_f of the V_O - O_i defect is also significantly reduced by La doping. Hence, the greater ease of its formation in the La-doped HfO_2 may explain the slow-down in PBTI recovery observed, as well as the increased susceptibility of the La-

doped HfO₂ to stress induced degradation at a high oxide stress field.

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