IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 41, NO. 6, DECEMBER 1994

Time Dependence of Switching Oxide Traps

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Abstract

Metal-oxide semiconductor field-effect transistors (MOSFETs) were irradiated and then annealed under alternating positive and negative bias. The magnitude of the reversible trapped-oxide charge component decayed over the course of several cycles (of 3×10^3 s each) in one of two processes studied. The HDL hole trap model is shown to explain these and other recent results.

I. INTRODUCTION

Over the years, a great many terms have been applied to the compensated (not permanently "annealed") hole trap, for example, near interfacial hole trap, annealed hole trap, oxide trapped charge, interface trap (state), slow state, anomalous positive charge (APC), E′ center, oxygen vacancy, strained (broken) Si-Si bond, border trap, neutral electron trap, and electron trap. This confusion has resulted in large part because different experimenters using different techniques have observed the same basic effect in different contexts.

In this paper, we will review the basic hole trap model that our group at the former Harry Diamond Laboratories (HDL) — now the Army Research Laboratory (ARL) — initially proposed six years ago [1-3] (providing a simple explanation of both permanent annealing and the "reverse annealing" phenomenon). We will also present new evidence and discuss how the model explains other recent results in the literature, specifically, the compensation effects in thermally stimulated current (TSC) measurements, the behavior of the neutral electron trap (NET), and some experiments purporting to show the conversion of trapped holes into interface traps. In addition, we will also discuss the terminology of *border traps*.

Recent work has attributed the first two post-irradiation effects (permanent annealing and charge switching) to a two-defect model [4], in which the permanent annealing is due to the traditional hole trap (which anneals but does not switch) and a second "anomalous" positive charge (APC) (which switches but does not anneal) [4]. We will provide examples from our data indicating that this distinction is not a clear one. In addition to these electrical measurements, we will consider the merits of this other hypothesis in light of ESR results seen and not seen.

II. BACKGROUND

A. HDL Hole Trap Model

Following several works which reported, as an aside, the curious negative reversibility under negative bias of oxide trapped charge previously annealed under positive bias [5-7], we performed several detailed studies [1,2] of this phenomenon and proposed what we will refer to as the HDL model. This model was based upon several key points. First, a large body of previous work [bibliography of Ref. 3] has provided convincing evidence that ionizing radiation depositing energy in the insulating oxide of a metal-oxide-semiconductor (MOS) device will create electron hole pairs, with some fraction of the holes escaping initial recombination. Under positive bias these holes will transport towards the substrate, where some percentage will become trapped in the oxide near the interface. These holes are not permanently trapped; they will "anneal" on an approximately logarithmic time scale at room temperature due to a tunneling mechanism, with the exact shape of the response curve depending on the specific spatial and energetic distribution of trapped holes [7]. Secondly, Feigl et al [8] identified the E′ center observed in unirradiated, bulk silicon dioxide, as a weak Si-Si bond owing to an oxygen vacancy between two Si atoms, each backbonded to three oxygen atoms. Thirdly, Lenahan et al [9] have shown that the E′ center and the radiation-induced trapped positive charge are the same defect; they found that the quantity of trapped positive charge measured electrically using capacitance-voltage (*C-V*) analysis corresponded to the number of E′ centers measured using molecular electron spin resonance (ESR) techniques. Of equal importance, they discovered during subsequent annealing experiments that the amount of trapped charge diminished at the same rate as the strength of their E′ signal. Finally, there is the evidence of the negative bias "reverse annealing" itself.

Figure 1 shows the now familiar diagram for the HDL model [2]. Figure 1(A) depicts the precursor site with the strained Si-Si bond. A key point is that the strain between the two Si atoms is probably not the same for all E′ centers. This will be discussed in more detail in the next section. Following the breaking of the weak bond by the radiation-induced hole, the positively charged Si atom (with the trapped hole) moves away from the uncharged Si atom (with a now-dangling bond — unpaired spin). The positively charged Si atom then relaxes back into a planar configuration (shown in Figure 1(B)). A second key point is that since the local bond strains are not the same, the separation distance between the two Si atoms will not be the same either. The results of Lenahan et al require that the amount of detectable charge decrease at the same rate as the number of unpaired spins. This point is crucial. Assuming that the E′ center *is* the radiation-induced hole trap, Figure 1(C) is the simplest and most reasonable explanation for their results. An electron tunneling into the oxide from the substrate can eliminate *both* the positive charge and the unpaired spin if it is trapped by the previously neutral Si atom. (If the electron tunneled to the positively charged Si, then the number of unpaired spins would *increase*.) Next, if the trapped hole is only compensated by this trapped electron, then the process of "reverse annealing" can be readily understood, simply requiring that one of the two electrons on the now negatively charged Si atom tunnel back to the substrate (returning to the configuration of Figure 1(B)). The observation that some traps can be alternately filled and emptied is depicted by the arrows going both ways between Figures 1(B) and 1(C). The bond between the Si atoms can also be reformed, reflecting true annealing of the defect instead of compensation (long arrow back to Figure 1(A)).

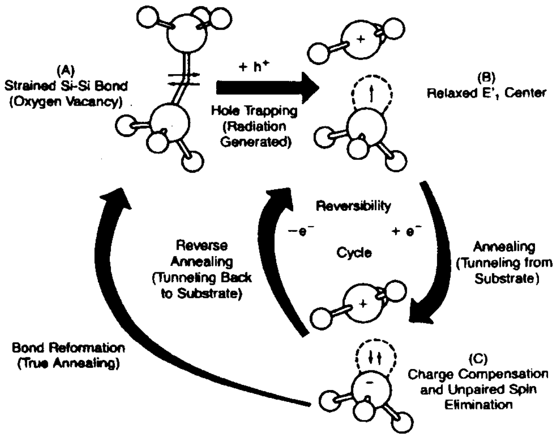

Fig. 1 The HDL Hole Trap Model.

B. Dependence on Local Lattice Strain

Various subtleties in the "reverse annealing" response can be understood if we consider the differences in the strain and subsequent separation distance between the two Si atoms of different E′ centers. These differ between processes, as well as with distance in a given oxide.

In the original development of our model, we relied on the picture of the oxide and interface region developed by Deal and co-workers in the 1960's [10]. At the interface, where oxidation is occurring, there is a high degree of local strain because of the lattice mismatch between Si and SiO_2. Since the oxidation is not complete initially, there is also a high concentration of excess Si. As the oxidation proceeds, the interface moves into the substrate and excess oxygen diffuses in from the oxide/vacuum surface. In effect, the excess Si diffuses into the oxide, where it is consumed by the oxidation process leading to a gradient in the excess Si concentration. Because of the flexibility of the Si-O bonds, the strain from the lattice mismatch is also accommodated. This picture is reinforced by the x-ray photoelectron spectroscopy (XPS) work of Grunthaner et al [11]. We proposed [1,2] that the behavior of a positively charged hole trap would depend on the local strain. When the Si-Si bond is broken, the positively charged Si relaxes toward the plane of the oxygen atoms (some would say even beyond it) [8]. If the complex is neutralized by the tunneling of an electron (Figure 1(C)) there will be an electrostatic force, tending to bring the Si atoms together, reforming the broken bond. In a highly strained region, near the interface, the separation between the Si atoms will be greater because they are pulled farther apart. Hence the defect will be more stable. In a less strained region, the Si atoms will be closer together and the bond will be more likely to reform. Both the case where the bond reforms and the case where it does not are fundamental to our discussion. We have always recognized the statistical nature of the process, which we attribute to a distribution of separation distances between the two Si atoms.

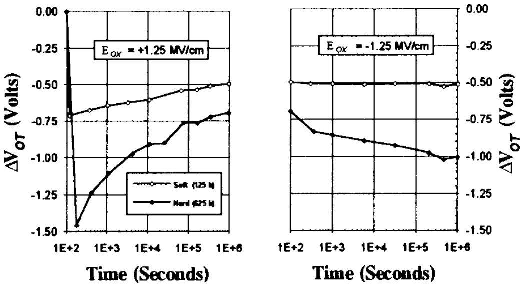

Fig. 2 Comparison of reversible switching characteristics for a radiation "hard" versus "soft" MOSFET.

This effect of the difference in separation distances is illustrated in Figure 2 [1], which compares the "reverse annealing" response for two differently processed oxides. The sample on the bottom underwent a "hardened" process (no high temperature post-oxidation anneal (POA)), whereas the sample on the top was fabricated with a "soft," commercial process (half-hour high temperature POA). These samples were actually processed identically on the same line, except that they received different POA treatments. The high temperature POA means the oxide is kept at the oxidation temperature in an inert ambient for 30 minutes. This temperature is high enough that it can be used to reflow glass, so it is reasonable to think that oxygen vacancy point defects near the interface are free to diffuse into the bulk during the POA (which also relieves high local strain). The "soft" oxide appears softer than the "hard" oxide because the traps are more stable (that is, they anneal more slowly farther from the interface), not necessarily because it contains more traps [7]. The hard oxide, with more excess Si near the interface, exhibits more charge switching behavior, as one would expect. In addition, the broken Si-Si bonds might be less likely to reform in the oxide without the POA, since the lattice strain is accommodated over a relatively short distance, resulting in greater local bond strain, and thus greater separation distance between Si atoms.

C. Theoretical Considerations

Our model was originally proposed as the simplest explanation for a variety of experimental results. For a time, we puzzled over why the electron would tunnel to the "wrong" Si, in spite of the coulomb repulsion, but we never developed what we considered to be a good answer. Our own experimental results can be explained equally well with the extra electron going to either Si, and we considered both possibilities. The model we ultimately proposed was highly influenced by the work of Lenahan et al [9], but several other experimental results since then (which we will discuss shortly) have reinforced this view. However, even if our model is completely correct empirically, we still view it as useful for someone to develop the underlying theory to explain why things work the way they seem to work.

III. EXPERIMENTAL PROCEDURE

We examined two different sets of n-channel closed geometry metal-oxide-semiconductor field-effect transistors (MOSFETs), each from a different U.S. manufacturer. The devices from Process A have a gate oxide thickness of 35 nm and a channel length of 1.2 μm, and were irradiated to a total dose of approximately 600 krad(SiO_2). These devices underwent the same process as the sample with the hard oxide from Figure 2. Devices from Process B, a soft commercial process (different from the process that produced the sample with the soft oxide of Figure 2), have a gate oxide thickness of 20 nm and a channel length of 0.7 μm, and were irradiated to a total dose of approximately 100 krad(SiO_2). The dose rate in each case was 100 krad(SiO_2) per min, supplied by a 10 keV x-ray tester.

Following irradiation, both sets of samples were annealed under positive bias (producing an external applied electric field of +1.25 MV/cm); after some time, the bias was switched negative. These cycles were repeated several times. During the annealing, the devices were monitored on average twice per decade of time using an HP4145B parametric analyzer to record drain current (with 0.15 V applied to the drain) versus applied gate voltage (I_D-V_G) characteristics. We subsequently applied the standard subthreshold charge separation technique [12] to resolve ΔV_{TH} into oxide trapped charge (ΔV_{OT}) and interface trapped charge (ΔV_{IT}) components. We focused our attention on the oxide trapped charge component. The interface trap component was generally stable in comparison. (During the first switch to negative bias, the interface trap component increased 10 to 15 percent; subsequent bias switches produced a change of only a few percent.) Unirradiated control devices from Process A did not exhibit any noteworthy shifts under either positive or negative bias; controls from Process B had a small negative shift (about 15 mV) under negative bias, which was comparable to the negative shifts for the irradiated Process B samples.

IV. RESULTS

The crux of the two-defect APC hypothesis [4] is that there are two different species involved in the positive-bias annealing and negative-bias "reverse annealing" effects observed in numerous studies. Figure 3 shows the results of four similarly irradiated and annealed MOSFETs from Process A. One by one, the bias on each device was switched to negative (the first at 3 × 10^4 s, the second at 10^5 s, the third at 3 × 10^5 s, and the last at 10^6 s). Following the switch, each device was kept under negative bias for approximately 2 × 10^6 s before being switched to positive again. It is observed that following the re-application of positive bias, all four of the devices appear to approach saturation at about the same value. Therefore, it depends on when the device was switched to negative bias whether the pre-switch value of ΔV_{OT} is recovered (and surpassed) or not, in contrast to the APC hypothesis [4]. Figure 3 indicates that this effect can be an artifact of when the measurement is taken.

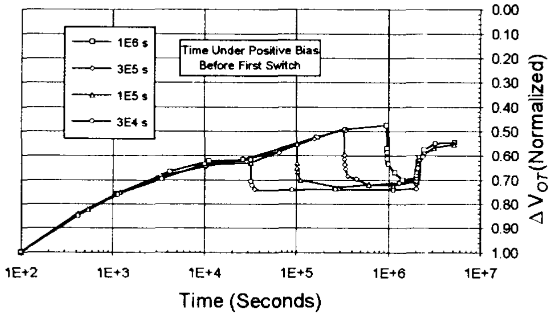

Fig. 3 A comparison of the normalized oxide-trapped charge-annealing results of four different n-channel MOSFETs from Process A, each switched to negative bias at different times. The time under negative bias is the same for each.

Figure 4 shows the ΔV_{OT} annealing results of a device from Process B following irradiation. The device was annealed under positive bias for 3 × 10^3 s and was then switched to negative bias for another 3 × 10^3 s. This procedure was repeated for two additional cycles. In this case, the positive annealing trend appears to be relatively undisturbed by the intermittent annealing under negative bias. In addition, the magnitude of the reversible element under negative bias appears to be constant. This result agrees with those of Freitag et al [4], and would appear to bear out their theory of a non-annealing reversible element. However, it should be noted that the magnitude of the switching charge is of the same order of magnitude as that for an unirradiated device from the same process (see Figure 5).

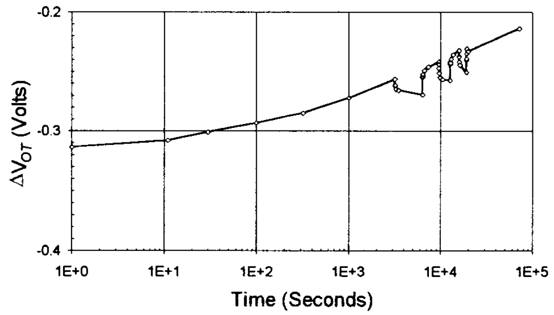

Fig. 4 The ΔV_{OT} annealing results for an n-channel MOSFET from Process B, subjected to alternating positive and negative bias cycles of 3×10^3 s each.

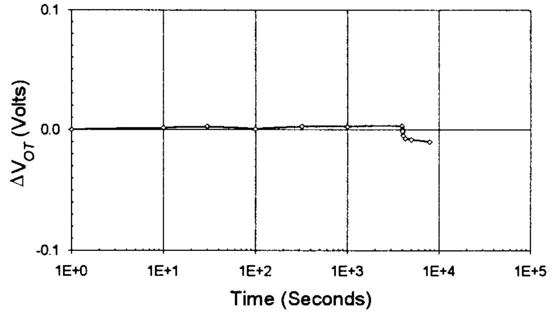

Fig. 5 The ΔV_{OT} bias stressing results for an unirradiated Control from Process B, subjected to alternating positive and negative bias cycles of 3×10^3 s each.

Figure 6 shows the results of a similar annealing experiment on a device from Process A. In this case, the initial pre-switch value of ΔV_{OT} is not recovered. More importantly, the magnitude of the reversible element is clearly decreasing with each cycle. This effect is more clearly seen in Figure 7, where the magnitude is plotted fresh with each cycle. Following the first switch, a reversal in ΔV_{OT} of 100 mV is observed. Following the second switch, the reversal is only 50 mV. The third switch results in little more than 30 mV. This result clearly contradicts the notion that the "APC" switches, but does not anneal at room temperature. In this case, the control did not exhibit any shift (see Figure 8), but the ΔV_{IT} component of the irradiated sample did increase somewhat during the first negative switch. It was relatively flat thereafter.

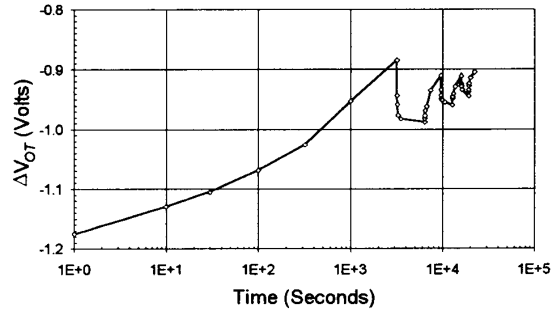

Fig. 6 The ΔV_{OT} annealing results for an n-channel MOSFET from Process A, subjected to alternating positive and negative bias cycles of 3×10^3 s each.

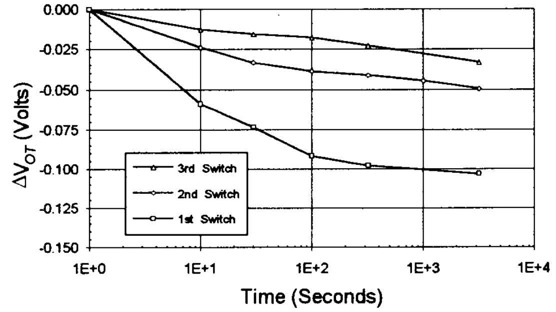

Fig. 7 A comparison of ΔV_{OT} versus time for each of the three different cycles under negative bias for the n-channel MOSFETs from Process A shown in Figure 6.

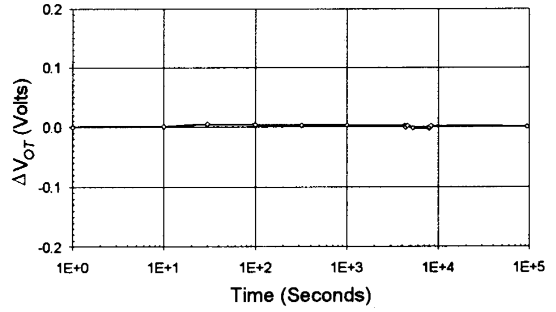

Fig. 8 The ΔV_{OT} bias stressing results for an unirradiated Control from Process A, subjected to alternating positive and negative bias cycles of 3×10^3 s each.

Qualitatively similar switching results were observed for another Process A device when switching the bias every 10^5 s instead of every 3×10^3 s (see Figure 9). In this case, the magnitude of the decaying reversible element has a larger initial value. Figure 10 shows the charge separation results for the sample in Figure 9. The interface trap component, ΔV_{IT}, is seen to increase when the bias is switched negatively for the first time, and then to remain relatively stable thereafter. The threshold voltage response (middle curve) indicates that, even taking the ΔV_{IT} shift into account, the magnitude of the switching component does decrease over time. This may be an indication that we are indeed observing "true annealing" of some E′ centers on this time scale.

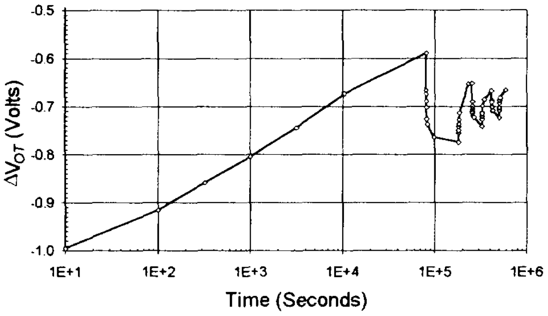

Fig. 9 The ΔV_{OT} annealing results for an n-channel MOSFET from Process A, subjected to alternating positive and negative bias cycles of 1×10^5 s each.

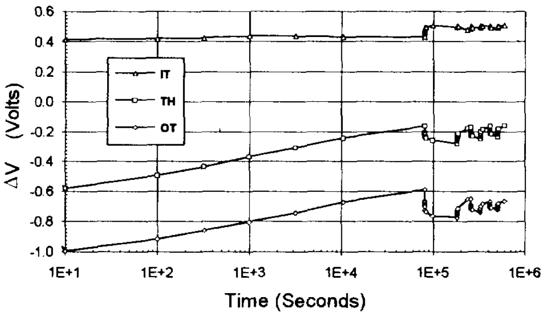

Fig. 10 Charge separation calculations for the annealing results of Figure 9.

V. DISCUSSION

The HDL model for the hole trap, discussed above, provides a simple and reasonable explanation for these results. First, electrons have to tunnel in before they can tunnel back out. Assuming that the "reverse annealing" proceeds via a tunneling mechanism, the sites closest to the interface will lose their extra charge first. If the device has been annealed previously under positive bias for a longer period of time, then more charge will be available deeper into the oxide to subsequently "reverse anneal". Secondly, the decrease in the switchable element is quite possibly due to the permanent, "true" annealing of some of the hole traps that were previously only compensated (Figure 1(C) to Figure 1(A)).

The HDL model was initially presented in 1988, successfully accounting for the two main features of the experimental data available at that time. These are permanent annealing, which we interpret as reformation of the broken bond, and the "reverse annealing" (or switching), which we interpret as a defect site exchanging charge with the Si substrate by tunneling. Since we presented the model, however, it has become clear that this model can also account for four other experimental effects which either are more recent or had been reported previously but not adequately explained. These effects, along with the original two, are listed in Table I. We will now discuss each of these in some detail.

Table I
Effects Explained by HDL Hole Trap Model

1	Permanent annealing of broken Si-Si bonds
2	Switching behavior of trapped holes near the interface due to tunneling
3	Compensation effects observed in TSC measurements
4	Net electron trapping from NETs
5	NET annealing
6	Apparent "conversion" of trapped holes to interface traps

A. TSC Measurements

In TSC measurements, trapped charge is thermally detrapped by applying a gradual temperature ramp to the sample. The current that flows is recorded as a function of temperature, providing spectroscopic information about the trapped charge. In 1988, Shanfield et al [13] performed TSC measurements which were later published. They reported that for a soft oxide the integrated current was *less* than the trapped charge indicated by C-V measurements. On the other hand, for a hard oxide the integrated current was *more* than the trapped charge indicated by C-V measurements. At an informal working group meeting in September of that year, one of us (Oldham) interpreted these results in light of our model. A key point in the analysis was that we had worked with the same two oxides in developing the model — in fact, they are the same two oxides shown in Figure 2. Oldham argued that the TSC results for the hard oxide were consistent with the compensating electron traps we observed — the trapped holes were really there, but not detected by a C-V measurement because of compensating electrons. For the soft oxide, space charge effects clearly reduced the TSC signal from the "correct" amount. But for this oxide, no compensation effects were observed in our experiments, so

Q_{CV} and Q_{TSC} should agree if space charge effects were accounted for.

Subsequently, Fleetwood et al [14-16] replicated the TSC measurements of Shanfield et al [13] using different samples. They confirmed that significant compensating electron trapping occurred in their hardened oxide, and that Q_{TSC} was greater than Q_{CV} for this reason. For their soft oxide, they also reported that Q_{TSC} was essentially equal to Q_{CV} at fields large enough to overcome space charge effects. These results are all consistent with our model.

B. NET Results

Walters et al [17] proposed that the neutralized hole trap, that we had proposed for the case where the broken Si-Si bond is not reformed, *is* the neutral electron trap — that this center can, under appropriate conditions, capture a second electron and become net negative. He was inspired to propose this idea, both by our model and by much earlier work by Aitken et al [18], which suggested that the NET was an electric dipole. (Aitken later concluded that the neutral center is probably dipolar in nature, that it can trap both electrons and holes [19]. The capture cross-section for the second electron would then depend on the separation distance of the oppositely charged Si atoms.) Walters conducted a series of experimental investigations to test his proposal. He found that the spatial distribution of NETs matched the spatial distribution of trapped holes. Prior to Walters' work, most NET studies were carried out involving unbiased irradiations. The radiation conditions were chosen to simulate an x-ray lithography exposure, which is always done unbiased. The conventional picture was that standard annealing treatments could eliminate positive centers but not the NETs. Walters conducted his radiation exposures under bias and found that hole trapping was sensitive to bias as one would expect. He also found that the NET density correlated with the trapped hole density when the applied field was varied — a result which was unexpected. He concluded that his results were very consistent with our model, and that the dipole state we proposed is real and that it acts as the neutral electron trap.

C. Annealing of Trapped Electrons

One would expect that the negatively charged version of the E′ center as proposed by Walters would not be extremely stable. Thompson and Nishida [20] have performed hot electron injection experiments that led to significant charging of neutral electron traps. In addition, they have studied the decay of charged NETs back to the neutral state as a function of time, temperature, and applied field. Their results indicate that, in fact, the negative charge can be annealed fairly easily, which is consistent with our work and with that of Walters [17].

D. Trapped Hole Conversion to Interface States (Traps)

Several authors have reported experiments that they interpret as indicating that trapped holes are being converted directly to interface traps. Lyon and co-workers [21] have been probably the most persistent advocates of the idea of a direct conversion process. Their article [21] describes an experiment where they irradiated their samples at low temperature, then applied a high field to push the holes to the interface. They determined the spatial distribution of the trapped holes (their Fig. 2) from photon-assisted tunneling measurements. They then injected electrons to neutralize the trapped holes (or to "annihilate" them, in their words). After the electron injection, they concluded that the holes near the interface were converted to interface traps, and the holes farther away were simply eliminated.

These results are easily reconciled with the HDL model. The electron injection neutralizes all the positive charge (Figure 1(B)), leaving the defects as in Figure 1(C). Those traps close enough to the interface to exchange charge by tunneling do so when the bias is changed. Those defects too far from the interface to exchange charge remain electrically inactive in the neutral state (Figure 1(C)). Eventually, they may revert to the original state (Figure 1(A)), but there is no way to tell experimentally. The defects being called interface states by Lyon et al are really trapped holes which exchange charge by tunneling. How the E′-like centers are converted to interface traps has always been a major question in trapped hole conversion models. Once one recognizes the trapped hole remains a trapped hole, no mysterious transformation is necessary. Oldham et al [22] first proposed in 1989 that trapped holes exchanging charge with the substrate by tunneling were being interpreted as interface traps in these experiments.

In our experiments at room temperature, interface traps are in equilibrium with the substrate and charge moves in and out of them in response to small voltage changes. On the other hand, the trapped holes respond only to large bias changes — charge tunnels into the oxide under positive bias and out of the oxide under negative bias. Hence, in principle, one can distinguish trapped holes from real interface traps. In the work by Lyon et al [21], however, they used the Jenq technique to study the defects. As we understand this technique, the sample is cooled to liquid nitrogen temperature, which has the effect of freezing out the interface traps so that they are no longer in equilibrium with the substrate. The sample is biased into depletion, and a light source is used to create charge pairs to invert the interface region, which leaves the interface traps positively charged in an n-type sample. When the sample is ramped into accumulation, electrons flow in and charge the interface traps negatively. In other words, the interface traps at low temperature behave like trapped holes — responding to large bias changes, but not to small ones. For this reason, the Jenq technique is not effective at distinguishing between trapped holes exchanging charge by tunneling and true interface traps.

Thus there are really six effects observed in studies of trapped holes induced by radiation which are explained in a single, unified way by our model of the trapped hole; these effects are listed in Table I.

E. APC Hypothesis

This brings us to the work of Freitag et al [4], who report two kinds of electrical behavior — permanent annealing that they attribute to trapped holes, and switching behavior that they attribute to APC, following the nomenclature used by Trombetta [23-24]. Trombetta's description of APC is simply a positive center near the interface that exchanges charge with the substrate. This description is quite consistent with our model of the trapped hole. On the other hand, there is evidence that the APC observed by Trombetta and others when employing electron injection techniques is different form the radiation-induced hole trap. These traps appear to be highly influenced by the presence of hydrogen [25-26]. In addition, the number of electrons injected into the oxide are several orders of magnitude greater than the number of electrons created by ionizing radiation. To achieve the higher electron numbers would require radiation exposures on the order of Grads. Thus, the APC may indeed be a different trap than the radiation-induced hole trap that is the focus of our attention. The question is whether classical APC is present in these radiation studies.

In our view there are two fundamental problems with the position taken by Freitag et al [4] that two species of positive charge are present in their radiation work. First, they only consider two of the effects listed in Table I. Second, there is no direct ESR evidence for the existence of a second positively charged defect. The E' center has been shown to correlate very well with trapped positive charge in some experiments. In other experiments, the correlation between the E' signal and the trapped positive charge is much less compelling [24, 27-28]. However, none of these experiments involved radiation exposures or pure thermal gate oxides. We note that they all involve injection experiments with deposited oxides or even nitrided oxides. In addition, the calibration of ESR measurements is notoriously difficult, to the point that the calibration of a single measurement may be no better than a factor of two. Thus the lack of perfect correlation in some experiments is only to be expected. Furthermore, it is significant that the E' signal is the only defect detected. This lack of any other detectable signal along with the rough correlation of the E' signal with positive charge seems to clinch the identification.

ESR works by detecting unpaired spins. Any defect that changes charge state by gaining or losing one electron will have an ESR signature in either the charged or neutral state. If APC is really a separate defect, the fact that no paramagnetic defect has been identified that correlates with it indicates that APC can only work by gaining or losing two electrons at a time. This is a significant restriction, because it rules out many structures for the APC that one might otherwise be tempted to propose. We note that a center with this property, gaining and losing two electrons at a time, has been identified and studied successfully in Si_3N_4 by Lenahan et al [29]. In other words, such centers can be detected and identified when they really exist. But to our knowledge, no one has ever proposed that such a center plays a role in the radiation response of SiO_2, even though SiO_2 has been studied much more extensively than Si_3N_4. The question we ask is the following: If APC is really a separate defect, why can't its ESR signature ever be observed directly?

F. Border Traps (Switching Oxide Traps)

Finally, we believe it is useful to reexamine the nomenclature used to identify hole traps in the oxide that are merely compensated, and thus whose "annealing" is reversible. Such switching oxide traps close to the interface have often been mistaken for interface traps [22]. Recently, Fleetwood [30] proposed the name *border trap*.

Although this term is useful in visualizing the general location of these switching oxide traps, it is not the clearest description of these traps. For example, similar defects have different names. An E'_γ center 2 nm from the interface is a border trap, but the same center 4 nm from the interface is an oxide trap. And in between there is a region where the center could be either, depending on how fast the measurement is performed. The definition of what is or isn't a border trap depends on how the measurement is performed.

Therefore, our preference is to call switching oxide traps just that — *switching oxide traps*. This idea has the advantage that the traps are named based on their switching properties, as Fleetwood et al proposed [16]. In fact, the name *switching oxide traps* describes the traps and their electrical properties in a way that *border traps* does not. Furthermore, it is implicit in the name that a *switching oxide trap* switches in a particular experiment, so one need not often explain that the definition depends on how the measurement is done. And defects with similar structures in different parts of the oxide do not have completely different names. An E' center that switches is a switching oxide trap, and one that does not switch is a fixed oxide trap.

Finally, the name *switching oxide trap* is a smaller adjustment to the Deal convention. All traps are still oxide traps (whether switching or not) or interface traps. This is an important consideration because the Deal convention is widely used by communities much bigger than the radiation effects community. *Switching oxide trap* is a name closer to present standard use, so it probably has a better chance of being adopted outside of the radiation effects community.

VI. CONCLUSION

The radiation results we have shown are consistent with the hole trap model developed at HDL, involving a single defect to account for both the annealing and switching behavior observed. On the other hand, it is difficult to explain why what Freitag et al [4] have classified as APC would not continue to switch all of its charge with each switch in the bias. The HDL model anticipates that some previously switchable charge may in the future no longer switch.

In addition, we have reviewed the literature and demonstrated how the HDL hole trap model can readily explain various unrelated experiments. It is not clear whether the APC hypothesis can do so as well. Even more telling is that only one ESR signal, that of the E', has ever been identified for the radiation-induced hole trap. If the APC were really different, one would expect that after many years of study, someone would have observed it, in either its charged or uncharged state.

VII. REFERENCES

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