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The Role of Electron Transport and Trapping in MOS Total-Dose Modeling

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Abstract

Radiation-induced hole and electron transport and trapping are fundamental to MOS total-dose models. Here we separate the effects of electron-hole annihilation and electron trapping on the neutralization of radiation-induced charge during switched-bias irradiation for hard and soft oxides, via combined thermally stimulated current (TSC) and capacitance-voltage measurements. We also show that present total-dose models cannot account for the thermal stability of deeply trapped electrons near the Si/SiO_2 interface, or the inability of electrons in deep or shallow traps to contribute to TSC at positive bias following (1) room-temperature, (2) high-temperature, or (3) switched-bias irradiation. These results require revisions of modeling parameters and boundary conditions for hole and electron transport in SiO_2. The nature of deep and shallow electron traps in the near-interfacial SiO_2 is discussed.

I. INTRODUCTION

Figure 1 illustrates the traditional model of charge transport and trapping in irradiated thermal SiO_2 [1]. Ionizing radiation creates electron-hole (e-h) pairs in the SiO_2. The mobility of electrons that escape initial recombination is presumed to be high enough that they are typically swept out of the oxide in picoseconds [2]. Holes exhibit lower effective mobility, and transport dispersively toward the Si/SiO_2 interface for positive gate-to-substrate bias. There a fraction of the holes are trapped, with the remainder exiting into the Si. Trapped holes near the Si/SiO_2 interface can be annealed thermally, or annihilated or compensated via electron tunneling [1,3-6]. During the hole transport and/or trapping processes, hydrogen species (e.g., protons) are liberated in the bulk or near-interfacial SiO_2, transport to the interface, and react with hydrogen-passivated dangling bonds to form interface traps [7-10].

Recently, there have been several attempts to incorporate charge transport, trapping, and/or annealing processes into MOS total dose models [11]. Among issues addressed in numerical models of MOS oxide-trap charge are (1) bias and dose dependence [12], (2) effects of high-temperature thermal processing [13,14], (3) the profile along the bird's beak of a LOCOS isolation oxide [15], and (4) the magnitude and temperature dependence of thermally stimulated current (TSC) in irradiated SiO_2 [16]. In addition, similar modeling has been performed in an effort to aid the understanding of enhanced low-dose-rate gain degradation in bipolar base oxides [17] and back-channel leakage in SOI [18].

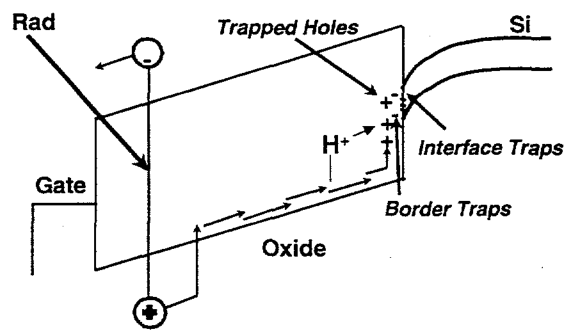

Figure 1. Schematic illustration of hole transport and trapping in irradiated thermal oxides. (After Ref. [1]).

One source of difficulty in total-dose modeling efforts is the inability to naturally incorporate compensating electron trapping near the Si/SiO_2 interface, which can act to offset trapped-hole space charge. This tends either to be neglected in present total dose models for thermal SiO_2, or else is incorporated in an *ad hoc* fashion [11-18]. The ability to properly account for electron trapping near the SiO_2 interface is of great interest because it has been demonstrated to (1) occur in a wide variety of thermal and nitrided oxides [3,6,19-21], (2) often have a density comparable to the trapped-hole density [19-21], (3) be difficult to distinguish from interface trap effects when the electrons are in border traps [19-25], and (4) play a key role in MOS parasitic elements responsible for the enhanced low-dose-rate sensitivity of bipolar base oxides [26,27].

In a recent study [28], TSC and capacitance-voltage (C-V) measurements on 45 nm thermal oxides demonstrate an unexpectedly high thermal stability for trapped electrons near the Si/SiO_2 interface. As illustrated in

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Fig. 2, electrons in deep traps are more resistant to thermal annealing than electrons in shallow traps, even for high-temperature annealing at negative bias. However, these deeply trapped electrons are removed at still higher temperatures during TSC measurements consisting of a ramp from 25°C to ~ 350°C at –12 V in ~ 1 h. That deeply trapped electrons in SiO_2 are stable to at least 125°C, but are removed by further annealing at higher temperatures, makes it difficult to understand why these electrons evidently do not transport across the oxide and contribute to the measured TSC under positive bias in previous work [20,29,30].

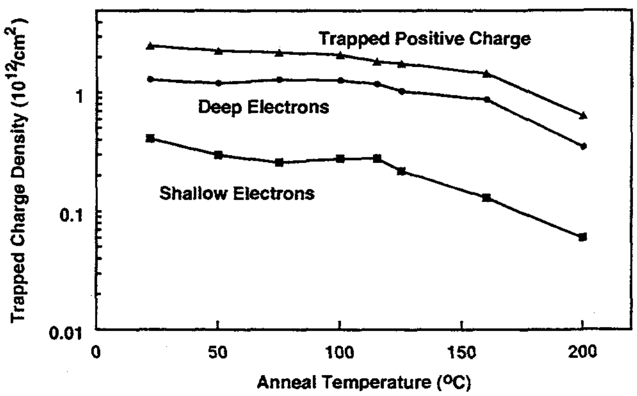

Figure 2. Trapped charge densities for 0.0053 cm^2 capacitors with 45 nm radiation-hardened oxides irradiated to 2.0 $Mrad(SiO_2)$ with 10 keV x rays at 10 V and 1100 $rad(SiO_2)/s$, and isochronally annealed for 15 minutes at –10 V. The trapped positive charge density was estimated from the integrated TSC; the density of deeply trapped electrons was estimated from combined TSC and C-V measurements; and the density of shallow electrons was estimated via high-frequency C-V hysteresis measurements. (After Ref. [28].)

In past TSC studies, MOS capacitors were usually irradiated at room temperature at constant bias. In this paper, we extend these data to include irradiation at elevated temperature, and under switched bias conditions, to determine whether de-trapping and transporting electrons contribute to the TSC under different experimental conditions. In fact, we see no such contributions. We show that these results require modifications to present total-dose models; at a minimum, the boundary conditions for hole transport and the mobilities assigned to some electrons in SiO_2 must be refined. Possible physical models are discussed for deep and shallow electron traps in the near-interfacial SiO_2.

II. ELEVATED TEMPERATURE IRRADIATION

Figure 3 shows TSC measurements at ± 12 V bias for 0.0052 cm^2 *n* substrate capacitors with 45 nm oxides irradiated to 2.0 $Mrad(SiO_2)$ at 80°C. The negative-bias TSC is shown in the top half of the figure. Here the solid circles denote the as-measured current after irradiation, and the open circles are the background leakage measured before irradiation. The triangles denote the net TSC due to transporting charge, which is the difference of the post- and pre-irradiation curves. The integrated TSC, corrected for background leakage, provides an estimate of the total oxide-trap charge density projected to the Si/SiO_2 interface ΔN_p. Effective densities of deeply trapped electrons ΔN_{ed} were estimated from combined TSC and high-frequency C-V measurements [19-21,28]. Effective densities of shallow trapped electrons were estimated via C-V hysteresis [20,28]. For the devices of Fig. 3, ΔN_p after 80°C irradiation was 2.3 x 10^{12} cm^{-2}; ΔN_{ed} was 2.0 x 10^{12} cm^{-2}; and ΔN_{es} was 0.45 x 10^{12} cm^{-2}. Comparing these results with postirradiation values in Fig. 2, the densities of trapped holes and shallow electrons are comparable for 20°C and 80°C irradiations, but the deeply trapped electron density increases by ~ 50% for 80°C irradiation [28,29].

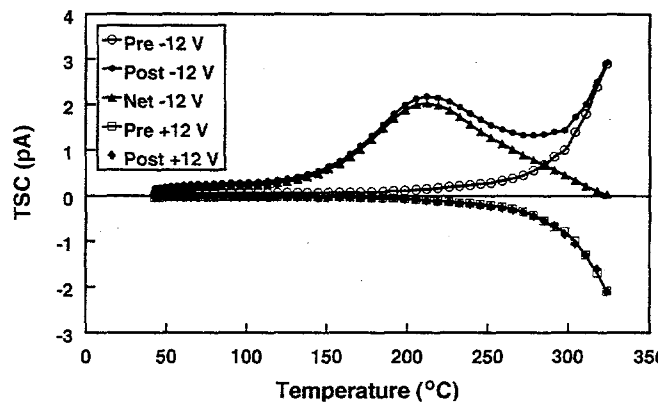

Figure 3. Negative (upper half) and positive (lower half) bias TSC for 45 nm radiation-hardened oxides irradiated to 2.0 $Mrad(SiO_2)$ at 1100 $rad(SiO_2)/s$ at a bias of 10 V at 80°C.

Despite the presence of a trapped electron density comparable to that of the trapped-hole density after irradiation, there is negligible positive-bias TSC due to charge detrapping and transport in the lower half of Fig. 3; that is, the current before and after irradiation is identical for +12 V TSC. Similar results are obtained for devices irradiated at positive and negative bias at temperatures up to 150°C. Thus, neither shallow nor deeply trapped electrons near the SiO_2 are free to transport across the oxide during TSC measurements, consistent with previous results for room-temperature irradiation or high field stress [20,30,31].

Asymmetries in TSC response like that in Fig. 3 have been explained by assuming the trapped electrons near the Si/SiO_2 interface lie primarily in border traps, which only exchange charge with the Si [19-21,23]. But the remarkable stability of the trapped electrons in Fig.

2 and Ref. [28] suggest that this conclusion must be re-evaluated, as discussed further below.

III. Switched-Bias Irradiation

The results of Figs 2 and 3 and Refs. [20,28-31] establish the stability of trapped electrons to elevated-temperature annealing and the inability of these electrons to contribute to TSC under positive bias in thermal oxides. However, it is not known whether the majority of these electrons were trapped in the near-interfacial SiO_2 during irradiation, or whether they tunneled into or were injected into the SiO_2 from the Si in response to hole trapping near the interface. Another way in which one may anneal and/or compensate trapped positive charge in SiO_2 is by switching the bias from positive to negative or zero during irradiation [32]. In this section we explore switched-bias irradiations for 45 nm radiation-hardened and 350 nm soft oxides.

For these switched bias irradiations, an excess of positive oxide-trap charge is initially created near the Si/SiO_2 interface via positive-bias irradiation. Upon reversing the irradiation bias to negative, holes are swept toward the gate, and electrons transport toward the Si. At very large negative electric fields, very little of the trapped positive charge is annihilated or compensated by the electrons [32], as the effective cross-section for electron capture by a trapped hole decreases dramatically with increasing oxide electric field [33]. However, trapped positive charge is neutralized quite efficiently at small negative electric fields during the second stage of switched-bias irradiation [32,34-36]. Below we separate the components of this neutralization into elements due to e-h annihilation, and due to compensation of trapped positive charge by electron trapping in the near-interfacial SiO_2. Such a separation has not been done in previous work on switched-bias effects in the literature [32,34-36]. We then determine whether the trapped electrons contribute to TSC under positive bias, as they must if they are able to de-trap and transport across the oxide. The contributions of deep and shallow electrons are not separated in this study, but it is known from prior work [21,28,29,37] that most electrons in these oxides lie in deeper traps.

A. *45 nm hard oxides.*

In Fig. 4, 0.01 cm^2 *n*MOS capacitors with 45 nm oxides are irradiated to 5.0 Mrad(SiO_2) at a dose rate of 5550 rad(SiO_2)/s and 5 V bias, with and without a subsequent 1.0 Mrad(SiO_2) exposure at –3 V. The TSC bias is –10 V for each case. The device without additional negative bias irradiation showed values of $\Delta N_p \approx 4.1 \times 10^{12}$ cm^{-2} and $\Delta N_e \approx 1.7 \times 10^{12}$ cm^{-2}, corresponding to a net oxide trap charge density $\Delta N_{ot} \approx 2.4 \times 10^{12}$ cm^{-2}. The device with the additional negative bias exposure showed $\Delta N_p \approx 3.2 \times 10^{12}$ cm^{-2}, $\Delta N_e \approx 2.6 \times 10^{12}$ cm^{-2}, and $\Delta N_{ot} \approx 0.6 \times 10^{12}$ cm^{-2}. Hence, roughly half the 1.8×10^{12} cm^{-2} decrease in ΔN_{ot} was caused by the annihilation of trapped holes during negative-bias irradiation, and half was caused by an accelerated buildup of electron trapping after the bias switch.

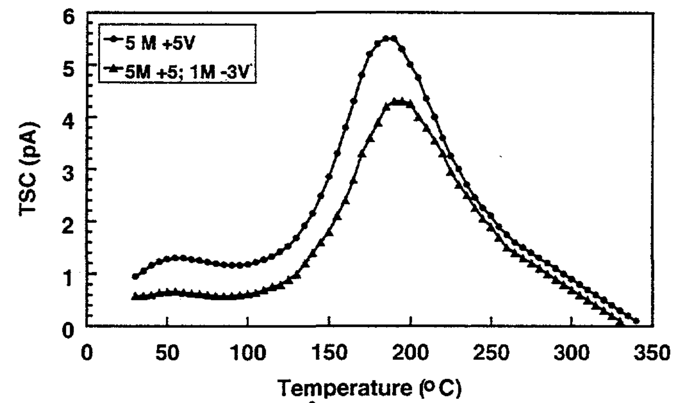

Figure 4. TSC for a 0.01 cm^2 capacitor with a 45 nm radiation-hardened oxide irradiated to 5 Mrad(SiO_2) at 5 V (dots), and for an identical device that received the same initial exposure followed by an additional 1 Mrad(SiO_2) irradiation at –3 V.

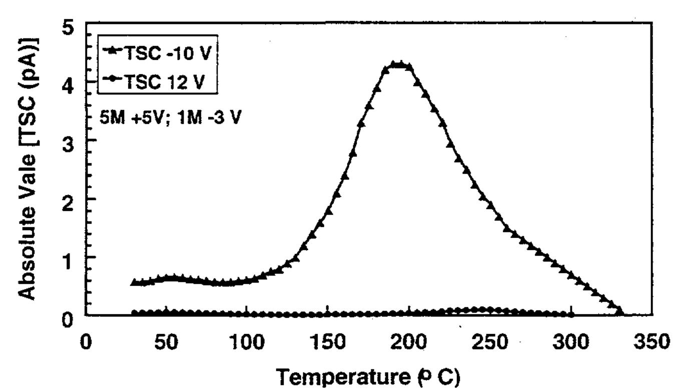

Figure 5. TSC at negative and positive bias for the devices and switched-bias irradiation conditions of Fig. 4.

In Fig. 5, the switched-bias results of Fig. 4 are compared with results for devices that saw an identical irradiation sequence, followed by TSC measurement at 12 V. Above we showed that the trapped electron density is ~ 80% as large as the trapped hole density after switched-bias irradiation. Thus, if the electrons are able to de-trap and transport across the oxide during positive-bias TSC, as the positive charge does during negative-bias TSC, one would expect only slightly less TSC for the positive-bias case than for negative bias. However, no significant current is observed for the positive-bias case in Fig. 5. Subsequent C-V and TSC measurements show that no net positive or negative charge remains in the oxide in either case in Fig. 5. So, despite our ability to trap a large number of electrons near the Si/SiO_2 interface during the negative-bias stage of the switched-bias irradiation in Figs. 4 and 5, these electrons do not transport across the SiO_2 after de-trapping.

B. 350 nm soft oxides.

We have also performed a similar series of experiments on 350 nm oxides that were given a 0.5 h, 1100°C N_2 anneal to deliberately increase their O vacancy density [13,14,19]. Figure 6 shows two of these capacitors irradiated to 5 krad(SiO_2) at 30 V with 10-keV x rays; one device received a second exposure to 15 krad(SiO_2) at –3 V. The device irradiated to 5 krad(SiO_2) without the –3 V irradiation showed $\Delta N_{ot} \approx 1.12 \times 10^{12}$ cm^2; $\Delta N_p \approx 1.21 \times 10^{12}$ cm^2; and $\Delta N_e \approx 0.09 \times 10^{12}$ cm^2. The device irradiated to 5 krad(SiO_2) at 30 V and 15 krad(SiO_2) at –3 V showed $\Delta N_{ot} \approx 0.51 \times 10^{12}$ cm^2; $\Delta N_p \approx 0.65 \times 10^{12}$ cm^2; and $\Delta N_e \approx 0.14 \times 10^{12}$ cm^2. Hence, of the 0.61×10^{12} cm^{-2} reduction in ΔN_{ot} for this device, 0.56×10^{12} cm^{-2} (92%) of the decrease occurs because of trapped-hole annihilation, and only 0.05×10^{12} cm^{-2} (8%) is due to additional electron trapping. This contrasts with the hardened 45 nm oxide of Figs. 4 and 5, where both e-h annihilation and electron trapping contributed significantly to the decrease in net oxide-trap charge density.

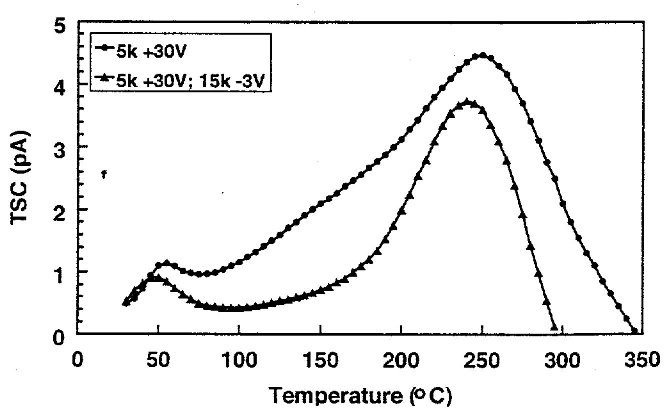

Figure 6. TSC for a 0.036 cm^2 capacitor with a soft 350 nm oxide irradiated to 5 krad(SiO_2) at 30 V (dots), and for an identical device that received the same initial exposure followed by an additional 15 krad(SiO_2) irradiation at –3 V. The TSC bias was –40 V.

By analogy to the results of Figs. 4 and 5, one might presume that, with much less electron trapping for the devices of Fig. 6 than for Fig. 4, there would be no significant TSC observable at positive bias. However, Fig. 7 shows the danger of this kind of analogy; the positive-bias TSC after switched-bias irradiation shows a broad peak at about 75°C. To understand the origin of this peak, in Fig. 8 we compare the TSC for the switched-bias case with an identical device irradiated to the same dose, i.e., 20 krad(SiO_2), but now at constant –3 V bias. Clearly, the two TSC curves are nearly identical. This result, as well as previous work on similar devices [21,30], strongly suggests that the TSC under positive bias in Figs. 7 and 8 is due to holes that are emitted from bulk trapping sites in these soft oxides, and not electrons transporting across the SiO_2. No such bulk trapping sites are present in the hard oxides of Figs. 4 and 5 [21].

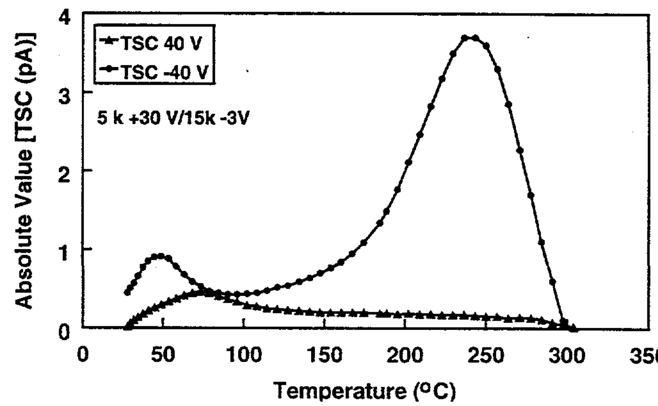

Figure 7. TSC at positive and negative bias for the devices and switched-bias irradiation conditions of Fig. 6.

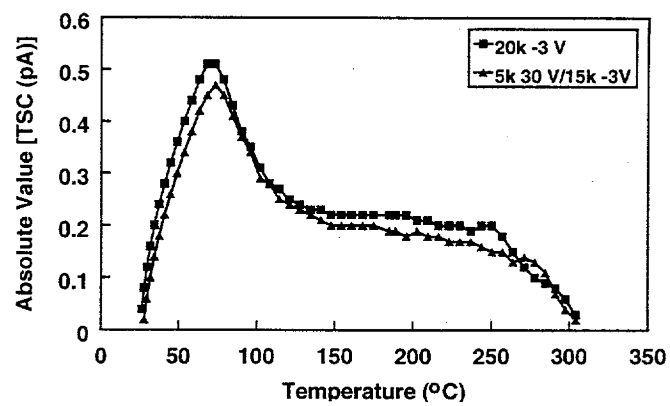

Figure 8. TSC for the switched-bias case of Figs. 6 and 7, and for an identical device irradiated to 20 krad(SiO_2) at –3 V. The TSC bias was 40 V in each case.

IV. DISCUSSION

The results of Figs. 2-8, as well as prior work in the literature [19-21,23,28,29], strongly suggest that the model of charge transport and trapping in Fig. 1 is not sufficiently complete to serve as the basis for a predictive model of total-dose radiation effects in SiO_2. We now discuss the key roles that electrons play in SiO_2 charge transport and trapping, and how these must be accounted for in total-dose models of thermal SiO_2. Here we focus on models of oxide-trap charge, for simplicity of discussion, though of course many of these factors also affect interface trap buildup [22,23,25].

When SiO_2 is irradiated, Fig. 1 shows the generation of an e-h pair, with the immediate escape of the radiation-induced electron. The high mobility that enables this carrier to escape the SiO_2 in picoseconds is characteristic of electrons that are generated with sufficient energy to reach the SiO_2 conduction band, and scatter few enough times before leaving the oxide to remain in the conduction band. The empty electron site resulting from the ionization event is refilled via site-to-site hopping transport of electrons in or near the valence band of the SiO_2, i.e., *hole transport*. The efficiency with which nearby atoms provide electrons to fill holes deeper within the SiO_2 during the "hole transport" process will depend on (1) the degree of overlap of the atomic orbitals, especially that of the O atoms [1], (2) the density of the SiO_2 [38,39], and/or (3) the densities of O vacancies and impurity atoms (e.g., H) in the SiO_2 [13,14,22,25]. Hence, these factors must be captured numerically and incorporated into total-dose models.

When transporting holes approach the Si/SiO_2 interface, one of four things can occur, as illustrated in Fig. 9. All must be considered when defining boundary conditions for total dose models. First, the hole may arrive at a location and energy level that facilitates the transfer of an electron from the Si to the near-interfacial SiO_2, thereby restoring charge neutrality in the oxide (#1 in Fig. 9). In the absence of defects and impurities in dense SiO_2 that cause hole and/or electron trapping, this is the natural progression of events.

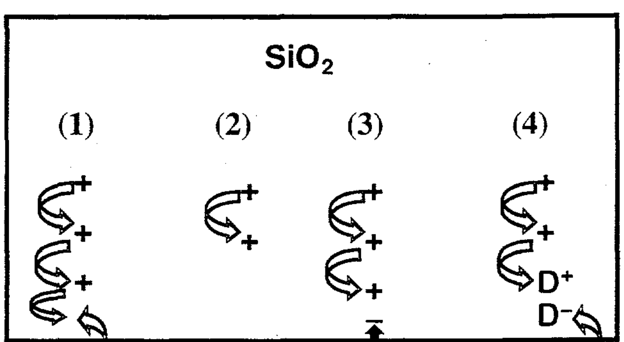

Figure 9. Schematic illustration of hole transport and trapping in SiO_2, ending with (1) e-h annihilation, (2) a trapped hole, (3) a trapped hole compensated by a shallow trapped electron, and (4) a stable near-interfacial dipole. In (2)-(4), the positive charge can transport across the oxide for negative-bias TSC, but the negative charge in (3) and (4) cannot contribute to positive-bias TSC.

The second possibility is that some holes encounter an O vacancy that stops further transport toward the Si; this is the classic deep hole trap in SiO_2 (#2 in Fig. 9) [1,13,14]. If the vacancy close enough to the interface, a shallow electron trap may be induced (#3 in Fig. 9). This possibility has been discussed by Lelis et al., and others [3,22,24,28]. There have been attempts to model this charge exchange via tunneling models [17,22,40], and in some cases this may be a viable approach. Complicating the situation, though, are many studies of random telegraph signals, which presumably also record the exchange of electrons with defects in SiO_2. These studies consistently report thermally activated charge exchange between the Si and the near-interfacial oxide, accompanied by lattice relaxation [41,42]. Simple tunneling kinetics are only seen below ~ 10 K [43]. Hence, for other devices, modeling the charge exchange between the Si and traps in the SiO_2 may require greater knowledge of both the defects involved and the lattice relaxation that accompanies the charge exchange.

The results of Figs. 2-8 and of Refs. [20,28-31] suggest another possible outcome (#4 in Fig. 9). A transporting hole near the Si/SiO_2 interface may reach a position and/or energy level that does *not* facilitate the transfer of an electron from the Si directly to a defect or ion having a missing electron. Hole transport induces lattice relaxation along its path, i.e., a small polaron [1]. Near the interface, the interaction of this polaron with a defect or impurity atom (e.g., suitable hydrogen species) can induce a trapping level that can capture an electron from the Si. This can be followed by lattice relaxation that shifts the energy level of the defect so the "deeply trapped" electron (or stable negative charge) can neither easily exit into the Si nor transport further into the SiO_2. This results in the formation of a dipole that consists of a trapped positive charge and a nearby negative charge at the wrong location and/or energy level to combine with the trapped positive charge. If the positive charge remains a trapped hole, and the negative charge remains a trapped electron, this is just a trapped exciton. However, given that an exciton may not be stable in the near-interfacial SiO_2 at or above room temperature, it seems likely that at least one of these species resides in an impurity complex in the near-interfacial SiO_2. For example, the positive charge could reside on a proton [25,39], a H_3O^+, or another over-coordinated O complex or related center [44]. The negative charge could reside on an OH^- or related center [25,45], or even H^- [46]. After the dipole is formed, the electrostatic driving force to annihilate the positive charge via electron tunneling from the Si is eliminated due to screening [27].

Figures 2-8 and other work [19-21,28,29] suggest the dipoles pictured in Fig. 9 (1) are stable at room temperature, (2) decay by releasing a hole for negative bias TSC (with loss of the electron to the Si), and (3) most likely decay via simple e-h recombination for positive-bias TSC. The latter process may be observable, e.g., via thermally stimulated luminescence measurements [47], which would be an interesting complementary study in the future. The density of these dipoles are affected by oxidation conditions, and/or H, N, and/or other chemical species in the near-interfacial SiO_2 [19,20]. That electrons do not transport across the oxide during positive-bias TSC is because the negative charge cannot enter the SiO_2 conduction band, or hop across the SiO_2 like holes do. Thus, the mobilities of electrons in SiO_2 depend strongly on their locations and energy levels. This must be factored into total dose models, especially for materials with many electron traps, like SOI or bipolar base oxides [27]. We expect this also to be a concern for some alternative dielectrics to SiO_2 [48,49].

V. CONCLUSION

Existing total dose models cannot account for the observations that (1) a large number of electrons are trapped in deep and shallow levels in the near-interfacial SiO_2, and (2) these electrons do not contribute to TSC under positive bias. To modify total dose models to include these effects will require refinements in the boundary conditions for charge transport and trapping in the near-interfacial SiO_2, and the incorporation of electron mobility values that depend on charge location and/or energy level. This latter point may be as simple as treating trapped and transporting electrons separately in the code, in contrast to the reversibility in transport exhibited by holes, or it may require a more sophisticated approach. To do this, future work must lead to a better understanding of the interactions between transporting holes and defects and impurity complexes in the bulk and near-interfacial SiO_2, as well as their impact on MOS radiation response and reliability.

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REFERENCES

[1] F. B. McLean, H. E. Boesch, Jr., and T. R. Oldham, "Electron-Hole Generation, Transport, and Trapping in SiO_2," in *Ionizing Radiation Effects in MOS Devices & Circuits*," T. P. Ma and P. V. Dressendorfer (Wiley, New York, (1989), pp. 87-192.

[2] R. C. Hughes, "Charge-Carrier Transport Phenomena in Amorphous SiO_2: Direct Measurement of the Drift Mobility and Lifetime," Phys. Rev. Lett. **30**, 1333 (1973).

[3] A. J. Lelis, T. R. Oldham, H. E. Boesch, Jr., and F. B. McLean, "The Nature of the Trapped Hole Annealing Process," IEEE Trans. Nucl. Sci. **36**, 1808 (1989).

[4] P. J. McWhorter, S. Miller, and W. Miller, "Modeling the Anneal of Radiation Induced Trapped Holes in a Varying Thermal Environment," IEEE Trans. Nucl. Sci. **37**, 1682 (1990).

[5] V. V. Emelianov, A. V. Sogoyan, O. V. Meshurov, V. N. Ulimov, and V. S. Pershenkov, "Modeling the Field and Thermal Dependence of Radiation-Induced Charge Annealing in MOS Devices," IEEE Trans. Nucl. Sci. **43**, 2572 (1996).

[6] V. S. Pershenkov, S. V. Cherepko, A. V. Sogoyan, V. V. Belyakov, V. N. Ulimov, V. V. Abramov, A. Shalnov, and V. Rusanovsky, "Proposed Two-Level Acceptor-Donor Center and the Nature of Switching Traps in Irradiated MOS Structures," IEEE Trans. Nucl. Sci. **43**, 2579 (1996).

[7] F. B. McLean, "A Framework for Understanding Radiation-Induced Interface States in SiO_2 MOS Structures," IEEE Trans. Nucl. Sci. **27**, 1651 (1980).

[8] M. R. Shaneyfelt, J. R. Schwank, D. M. Fleetwood, P. S. Winokur, K. L. Hughes, and F. W. Sexton, "Field Dependence of Interface-Trap Buildup in Polysilicon and Metal Gate MOS Devices," IEEE Trans. Nucl. Sci. **37**, 1632 (1990).

[9] D. B. Brown and N. S. Saks, "Time Dependence of Interface Trap Formation in MOS Devices as a Function of Oxide Thickness and Applied Field," J. Appl. Phys. **70**, 3734 (1991).

[10] R. E. Stahlbush, A. H. Edwards, D. L. Griscom, and B. Mrstik, "Post-Irradiation Cracking of H_2 and Formation of Interface States in Irradiated MOSFETs," J. Appl. Phys. **73**, 658 (1993).

[11] J. L. Leray, "Total Dose Effects: Modeling for Present & Future," 1999 IEEE NSREC Short Course, and references therein.

[12] V. Vasudevan and J. Vasi, "Numerical Simulation of Hole and Electron Trapping Due to Radiation in SiO_2," J. Appl. Phys. **70**, 4490 (1991).

[13] R. A. B. Devine, D. Mathiot, W. L. Warren, D. M. Fleetwood, and B. Aspar, "Point Defect Generation and Oxide Degradation During Anneal of the Si/SiO_2 Interface," Appl. Phys. Lett. **63**, 2926 (1993).

[14] P. M. Lenahan and J. F. Conley, Jr., "A Comprehensive Physically Based Predictive Model for Radiation Damage in MOS Systems," IEEE Trans. Nucl. Sci. **45**, 2413 (1998).

[15] C. Brisset, V. Ferlet-Cavrois, O. Flament, O. Musseau, J. L. Leray, J. L. Pelloie, R. Escoffier, A. Michez, C. Cirba, and G. Bordure, "Two-Dimensional Simulation of Total Dose Effects on NMOSFET with Lateral Parasitic Transistor," IEEE Trans. Nucl. Sci. **43**, 2651 (1996).

[16] P. Paillet, J. L. Touron, J. L. Leray, C. Cirba, and A. Michez, "Simulation of Multi-Level Radiation-Induced Charge Trapping and Thermally Activated Phenomena in SiO_2," IEEE Trans. Nucl. Sci. **45**, 1379 (1998).

[17] R. J. Graves, C. R. Cirba, R. D. Schrimpf, R. J. Milanowski, A. Michez, D. M. Fleetwood, S. C. Witczak, and F. Saigne, "Modeling Low-Dose Rate Effects in Irradiated Bipolar Oxides," IEEE Trans. Nucl. Sci. **45**, 2352 (1998).

[18] R. J. Milanowski, M. P. Pagey, L. W. Massengill, R. D. Schrimpf, M. E. Wood, B. W. Offord, R. J. Graves, K. F. Galloway, C. J. Nicklaw, and E. P. Kelley, "TCAD-Assisted Analysis of Back-Channel Leakage in Irradiated Mesa SOI nMOSFETs," IEEE Trans. Nucl. Sci. **45**, 2593 (1998).

[19] D. M. Fleetwood, S. L. Miller, R. A. Reber, Jr., P. J. McWhorter, P. S. Winokur, M. R. Shaneyfelt, and J. R. Schwank, "New Insights into Radiation-Induced Oxide-Trap Charge Through TSC Measurement and Analysis," IEEE Trans. Nucl. Sci. **39**, 2192 (1992).

[20] D. M. Fleetwood and N. S. Saks, "Oxide, Interface, and Border Traps in Thermal, N_2O, and Nitrided Oxides," J. Appl. Phys. **79**, 1583 (1996).

[21] D. M. Fleetwood, P. S. Winokur, L. C. Riewe, and R. A. Reber, Jr., "Bulk Oxide and Border Traps in MOS Capacitors," J. Appl. Phys. **84**, 6141 (1998).

[22] T. R. Oldham, F. B. McLean, H. E. Boesch, Jr., and J. M. McGarrity, "An Overview of Radiation-Induced Interface Traps in MOS Structures," Semicond. Sci. Technol. **4**, 986 (1989).

[23] D. M. Fleetwood, P. S. Winokur, R. A. Reber, Jr., T. L. Meisenheimer, J. R. Schwank, M. R. Shaneyfelt, and L. C. Riewe, "Effects on Oxide Traps, Interface Traps, and Border Traps on MOS Devices," J. Appl. Phys. **73**, 5058 (1993).

[24] D. J. DiMaria, D. A. Buchanan, J. H. Stathis, and R. Stahlbush, "Interface States Induced by the Presence of Trapped Holes near the Si/SiO_2 Interface," J. Appl. Phys. **77**, 2032 (1995).

[25] D. M. Fleetwood, W. L. Warren, J. R. Schwank, P. S. Winokur, M. R. Shaneyfelt, and L. C. Riewe, "Effects on Interface Traps and Border Traps on MOS Postirradiation Annealing Response," IEEE Trans. Nucl. Sci. **42**, 1698 (1995).

[26] D. M. Fleetwood, S. L. Kosier, R. N. Nowlin, R. D. Schrimpf, R. A. Reber, Jr., M. DeLaus, P. S. Winokur, A. Wei, W. E. Combs, and R. L. Pease, "Physical Mechanisms Contributing to Enhanced Bipolar Gain Degradation at Low Dose Rates," IEEE Trans. Nucl. Sci. **41**, 1871 (1994).

[27] D. M. Fleetwood, L. C. Riewe, J. R. Schwank, S. C. Witczak, and R. D. Schrimpf, "Radiation Effects at Low Electric Fields in Thermal, SIMOX, and Bipolar-Base Oxides," IEEE Trans. Nucl. Sci. **43**, 2537 (1996).

[28] D. M. Fleetwood, P. S. Winokur, O. Flament, and J. L. Leray, "Stability of Trapped Electrons in SiO_2," Appl. Phys. Lett. **74**, 2969 (1999).

[29] D. M. Fleetwood, P. S. Winokur, M. R. Shaneyfelt, L. Riewe, O. Flament, P. Paillet, and J. L. Leray, "Effects of Isochronal Annealing and Irradiation Temperature on Radiation-Induced Trapped Charge," IEEE Trans. Nucl. Sci. **45**, 2366 (1998).

[30] D. M. Fleetwood, R. A. Reber, Jr., and P. S. Winokur, "Effect of Bias on TSC in Irradiated MOS Devices," IEEE Trans. Nucl. Sci. **38**, 1066 (1991).

[31] R. A. Reber, Jr. and D. M. Fleetwood, "TSC Measurements of SiO_2 Defect Density and Energy in Irradiated MOS Capacitors," Rev. Sci. Instrum. **63**, 5714 (1992).

[32] D. M. Fleetwood, "Radiation-Induced Charge Neutralization and Interface-Trap Buildup in MOS Devices," J. Appl. Phys. **67**, 580 (1990).

[33] T. H. Ning, "High-Field Capture of Electrons by Coulomb-Attractive Centers in SiO_2," J. Appl. Phys. **47**, 203 (1976).

[34] V. D. Akhmetov, V. V. Bolotov, and A. Vishnyakov, "Quantitative Model for Charge Buildup in MOS Transistors Under Ionizing Radiation," Sov. Phys. Tech. Phys. **34**, 746 (1989).

[35] D. M. Fleetwood, P. S. Winokur, and L. C. Riewe, "Predicting Switched-Bias Response from Steady-State Irradiation," IEEE Trans. Nucl. Sci. **37**, 1806 (1990).

[36] V. S. Pershenkov, V. V. Belyakov, and A. V. Shalnov, "Fast Switched-Bias Annealing of Radiation-Induced Oxide-Trapped Charge and Its Application for Testing of Radiation Effects in MOS Structures," IEEE Trans. Nucl. Sci. **41**, 2593 (1994).

[37] D. M. Fleetwood, M. R. Shaneyfelt, W. L. Warren, J. R. Schwank, T. L. Meisenheimer, and P. S. Winokur, "Border Traps: Issues for MOS Radiation Response and Long-Term Reliability," Microelectronics Reliab. **35**, 403 (1995).

[38] J. L. Leray, "Activation Energies of Oxide Charge Recovery in SOS or SOI Structures After an Ionizing Pulse," IEEE Trans. Nucl. Sci. **32**, 3921 (1995).

[39] B. J. Mrstik, V. V. Afanase'ev, A. Stesmans, P. J. McMarr, and R. Lawrence, "Relationship Between Oxide Density and Charge Trapping in SiO_2 Films," J. Appl. Phys. **85**, 6577 (1999).

[40] T. R. Oldham, A. J. Lelis, and F. B. McLean, "Spatial Dependence of Trapped Holes Determined from Tunneling Analysis and Annealing," IEEE Trans. Nucl. Sci. **33**, 1203 (1986).

[41] K. S. Ralls, W. J. Skocpol, L. Jackel, R. Howard, L. Fetter, R. Epworth, and D. Tennant, "Discrete Resistance Switching in Submicron Si Inversion Layers: Individual Interface Traps and Low-Frequency (1/f?) Noise," Phys. Rev. Lett. **52**, 228 (1984).

[42] M. J. Kirton and M. J. Uren, "Noise in Solid-State Microstructures: New Perspective on Individual Defects, Interface States, and Low-Frequency (1/f) Noise," Adv. Phys. **38**, 367 (1989).

[43] J. H. Scofield, N. Borland, and D. M. Fleetwood, "Temperature-Independent Switching Rates for a Random Telegraph Signal in a Si MOSFET at Low Temperatures," submitted to Appl. Phys. Lett. (July 1999).

[44] W. L. Warren, K. Vanheusden, D. M. Fleetwood, J. Schwank, M. R. Shaneyfelt, and P. S. Winokur, "A Proposed Model for Positive Charge in SiO_2 Thin Films: Over-Coordinated Oxygen Centers," IEEE Trans. Nucl. Sci. **43**, 2617 (1996).

[45] E. P. O'Reilly and J. Robertson, "Theory of Defects in Vitreous SiO_2," Phys. Rev. B **27**, 3780 (1983).

[46] A. H. Edwards et al., late news, 1999 IEEE NSREC.

[47] M. Martini, G. Spinolo, and A. Vedda, "Phosphorescence and Thermally Stimulated Luminescence of Amorphous SiO_2," Solid St. Commun. **91**, 751 (1994).

[48] C. Chaneliere, S. Four, J. L. Autran, and R. A. B. Devine, "Comparison Between the Properties of Amorphous and Crystalline Ta_2O_5 Thin Films Deposited on Si," Microelectron. Reliab. **39**, 261 (1999).

[49] K. Lee, C. Kim, D. R. Ryu, J. Sim, B. S. Moon, K. Y. Kim, N. J. Kim, S. M. Yoo, H. Yoon, J. H. Yoo, S. I. Cho, "Low-Voltage, High-Speed Circuit Designs for Gigabit DRAMs," IEEE J. Solid-St. Ckt. **32**, 642 (1997).