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THE ROLE OF ELECTRON TRANSPORT AND TRAPPING IN MOS TOTAL-DOSE MODELING

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35-word Abstract

Deep and shallow electron traps form in irradiated thermal SiO_2 as a natural response to hole transport and trapping. The density and stability of these defects are discussed, as are their implications for total-dose modeling.

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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].

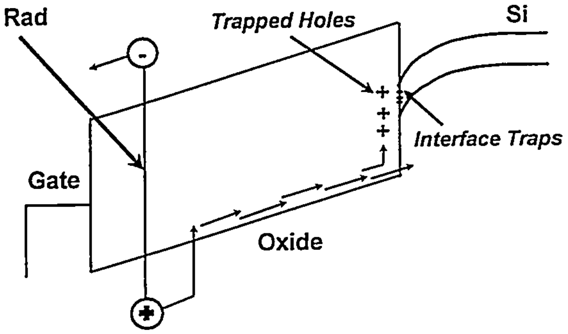

Figure 1. *Schematic illustration of hole transport and trapping in irradiated thermal oxides. (After Ref. [1]).*

Recently, there have been many attempts to incorporate charge transport, trapping, and annealing processes into models of MOS total dose response. Among issues addressed in numerical models of MOS oxide-trap charge are (1) bias and dose dependence [11], (2) effects of high-temperature thermal processing [12,13], (3) the profile along the bird's beak of a LOCOS isolation oxide [14], and (4) the magnitude and temperature dependence of thermally stimulated current (TSC) in irradiated SiO_2 [15]. 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 [16] and back-channel leakage in SOI [17].

A common source of difficulty in these total-dose modeling efforts is the inability to naturally incorporate compensating electron trapping near the Si/SiO_2 interface, which acts to offset the space charge of the trapped holes. This issue tends either to be neglected in present total dose models for thermal SiO_2, or else is incorporated in an *ad hoc* fashion [11-17]. The ability to properly account for electron trapping near the SiO_2 interface is of great interest because it has been demonstrated experimentally to (1) occur in a wide variety of thermal and nitrided oxides [3,6,7,18,19], (2) often have a density comparable to the trapped-hole density [18-20], (3) be difficult to distinguish from interface traps [21-24], and (4) play a key role in the enhanced low-dose-rate sensitivity of bipolar base oxides [25].

In this summary we illustrate examples from studies of TSC in thermal oxides that provide insight into the nature and stability of trapped electrons near the Si/SiO_2 interface. We find that electrons in deep traps tend to be more resistant to thermal annealing than electrons in shallow traps. Trapped electrons near the Si/SiO_2 interface do not contribute to TSC at positive bias, for either room temperature or elevated temperature irradiation. These results suggest modifications are needed to present total-dose models; in particular, the boundary conditions for hole transport and the mobilities assigned to electrons in SiO_2 must be refined.

Experimental Results

For all results in this summary, capacitors with radiation-hardened 45-nm oxides were irradiated with 10-keV x rays at a dose rate of 1100 rad(SiO_2)/s at ~ 20°C to 2.0 Mrad(SiO_2) at 10 V. Effective densities of *shallow* electron traps ΔN_{es} were estimated via room-temperature high-frequency (1 MHz) capacitance-voltage (C-V) hysteresis measurements [19,26,27] at a ramp rate of ~ 0.5 V/s. Effective densities of more deeply trapped electrons ΔN_{ed} were estimated from TSC and high-frequency C-V measurements (swept from negative-to-positive bias to exclude contributions of shallow trapped electrons) via [18,19]:

$$Aq\Delta N_{ed} = \Delta Q_p - C_{ox}\Delta V_{mg}\,. \qquad (1)$$

Here $\Delta Q_p = Aq\Delta N_p$ is the trapped positive charge obtained by integrating the TSC (corrected for parasitic leakage), $-q$ is the electronic charge, ΔN_p is the trapped positive charge density, C_{ox} is the oxide capacitance, A is the area, and ΔV_{mg} is the midgap voltage shift [18,19]. TSC measurements were performed under bias during a ~ 0.11°C/s ramp from ~ 20°C to 350°C [28].

To investigate the oxide-trap charge stability, 15-min isochronal anneals [29] were performed on some devices between irradiation and TSC measurement; results for 1 h isochronal anneals were similar. Figure 2 shows ΔN_p, ΔN_{ed}, and ΔN_{es} for devices irradiated to 2 Mrad(SiO_2) and annealed at −10 V at temperatures from 50 to 200°C before TSC measurement. The points at 20°C are controls for which no anneals were performed. After irradiation, the density of trapped positive charge was 2.5 x 10^{12} cm^{-2}; the density of deeply trapped electrons was 1.3 x 10^{12} cm^{-2}; and the density of shallow trapped electrons was 0.4 x 10^{12} cm^{-2}. Values of ΔN_p decrease with increasing anneal temperature, as expected. The density of shallow trapped electrons also decreases systematically with increasing temperature. In contrast, even though negative bias anneals might be expected to efficiently drive electrons out of the oxide, essentially no change is seen in ΔN_{ed} below 100°C.

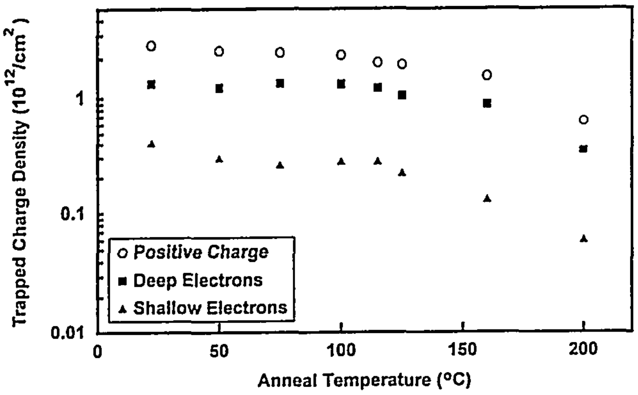

Figure 2. *Trapped charge densities after radiation exposure of 45-nm oxides to 2.0 Mrad(SiO_2) at 1100 rad(SiO_2)/s and 10 V, followed by 15-min isochronal annealing at −10 V.*

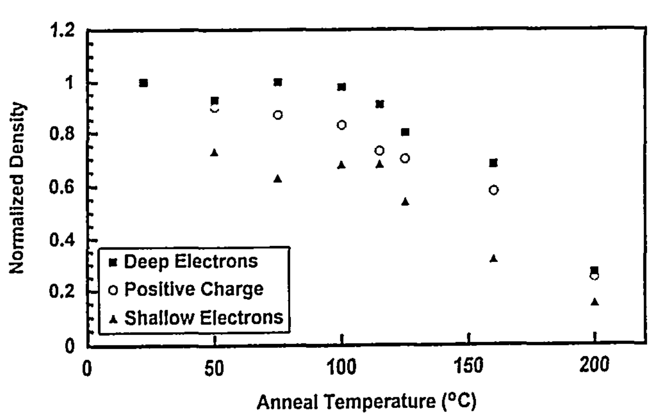

Figure 3. *Normalized trapped charge densities as a function of isochronal anneal temperature for the devices of Fig. 2.*

Figure 3 shows the relative stability of the deeply trapped electrons, the trapped positive charge, and the shallow electrons, normalized to postirradiation values. For 15-min 100°C anneal at −10 V, the density of deeply trapped electrons is unchanged from its postirradiation value, but the density of electrons in shallow traps has decreased by ~ 30 %. Note that the stability of the average trapped hole in Fig. 3 is greater than that of the shallow trapped electrons, but *less* than that of the average deeply trapped electrons. Results for other annealing biases and for effective interface-trap densities will be presented in the full paper.

It is also interesting to see how these quantities are affected by higher irradiation temperature. Figure 4 shows TSC measurements at ± 12 V bias for 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 net TSC at negative bias, along with C-V and hysteresis measurements, shows 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}. Hence, the densities of trapped holes and of shallow electrons are comparable for 20°C and 80°C irradiations, but the density of deeply trapped electrons increases by ~ 50% for 80°C irradiation. Despite the presence of a trapped electron density comparable to that of the trapped-hole density, there is negligible positive-bias TSC due to charge detrapping and transport in the lower half of Fig. 4; that is, the current before and after irradiation is identical for +12 V TSC. 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 [19,28]. Similar asymmetries in TSC response have been explained in the past by assuming that the trapped electrons near the Si/SiO_2 interface lie primarily in border traps, which only exchange charge with the Si [18-20,22]. However, the remarkable stability of the trapped electrons in Fig. 2 require that this conclusion be re-evaluated, as it is hardly meaningful to consider a trapped electron which is stable against 100°C annealing to be a border trap!

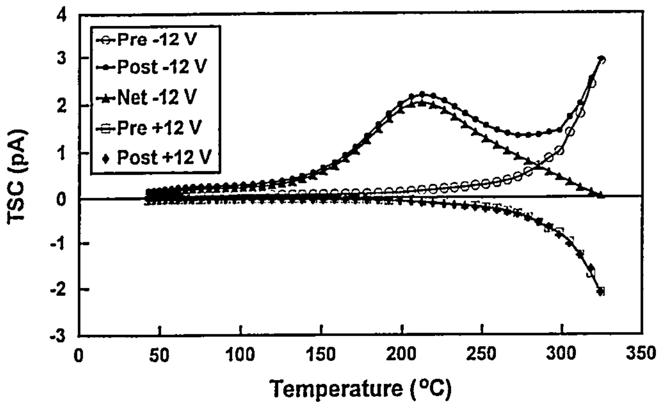

Figure 4. *Negative (upper half) and positive (lower half) TSC for 45-nm radiation-hardened oxides irradiated to 2.0 Mrad(SiO_2) at 1100 rad(SiO_2) at a bias of 10 V at 80°C.*

Discussion

The results of Figs. 2-4, and others to be presented in the full paper, suggest that the model of charge transport and trapping in Fig. 1 is not sufficiently complete to serve as the basis for a predictive total-dose model of radiation effects in SiO_2. We now discuss the key roles that electrons play in SiO_2 charge transport and trapping, and how these effects may be accounted for in an improved total-dose model for thermal SiO_2. In the summary, we limit our discussion to oxide-trap charge related issues. Interface traps will also be considered in the full paper.

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 electron 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 [30,31], and/or (3) the densities of O vacancies and impurity atoms in the SiO_2.

When transporting holes approach the Si/SiO_2 interface, one of three things can occur, all of which must be considered when defining boundary conditions for total dose models. First, the hole may present itself 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. In the absence of defects and impurities in dense SiO_2, this is the natural progression of events. However, some holes encounter an O vacancy that inhibits further transport toward the Si; this is the classic deep hole trap in the SiO_2 [1,12,13]. An associated shallow electron trap may result from the metastable exchange of charge between the Si conduction band and the Si atom which sits opposite to the deep hole trap, as envisioned by Lelis et al., for example [3,21].

The results of Figs. 2-4 suggest a third possible outcome. A transporting hole near the Si/SiO_2 interface may lie at a position and/or energy level that does *not* facilitate the transfer of an electron from the Si directly to the defect having the missing electron. Recall that hole transport induces lattice relaxation along its path in the form of a small polaron. Near the interface, the interaction of this small polaron with a defect or impurity atom (e.g., hydrogen species) can create a trapping level that can capture an electron from the Si, followed by a lattice relaxation after electron capture that shifts the energy level of the defect. This results in the formation of a dipole near the interface that consists of a trapped hole and an electron in the wrong location and/or energy level to annihilate the trapped hole (e.g., an exciton). After the dipole is formed near the interface, the electrostatic driving force to annihilate the hole via electron transfer from the Si is eliminated due to screening effects [25]. Figures 2-4 and other data we will show in the full paper suggest these dipoles (1) are quite stable at room temperature, (2) decay by releasing a hole under negative bias TSC, and (3) decay via e-h recombination under positive bias TSC. The latter process may be observable, e.g., during thermally stimulated luminescence measurements [32]. That electrons do not instead transport across the oxide during positive-bias TSC is because these electrons are not in the conduction band of the oxide, and have much lower mobility as a result. This reinforces the point that one may *not* assign the same, high value of mobility to all electrons in SiO_2.

Summary

Electron transport and trapping play a key role in the ionizing radiation response of thermal SiO_2. Deep and shallow electron traps form in response to hole transport and/or trapping. The density and stability of deeply trapped electrons greatly exceed those of shallow electrons in the devices studied here. These results provide insight into the definition of improved total dose models for MOS devices. In the full paper, experimental data will be shown for other annealing conditions, and the role of hydrogen in charge transport and trapping processes will be examined in more detail. Implications for the radiation response and reliability of ultrathin oxides will also be addressed.

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