Charge Trapping and Transport Properties of SIMOX Buried Oxides with a Supplemental Oxygen Implant*

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Abstract

The radiation response characteristics of single- and multiple-implant SIMOX (separation by implantation of oxygen) buried oxide layers that had received a supplemental oxygen implant and anneal step were measured as a function of temperature and time after exposure to short radiation pulses. A fast capacitance-voltage technique was used for these measurements. The results indicate that, in comparison to standard SIMOX, the supplemental-implant SIMOX buried oxide shows hole motion through the oxide, greatly reduced bulk hole trapping, and little or no bulk *shallow* electron trapping. Substantial *interfacial* hole trapping was observed in these materials, as well as *deep* electron trapping in the single-implant material.

I. Introduction

Silicon-on-insulator (SOI) buried oxides prepared by the SIMOX (separation by implantation of oxygen) process have been shown to contain a high density of both deep hole traps and shallow electron traps, in contrast to standard gate oxides produced by direct free-surface thermal oxidation [1–4]. The hole traps pose a problem for the radiation hardening of SIMOX layers, while the electron traps may contribute to oxide leakage current conduction. The major differences between thermal oxides and SIMOX oxides have been attributed to oxygen deficiency or excess silicon in the SIMOX buried oxide (BOX) layer. The dominant hole trap identified in the SIMOX BOX after exposure to ionizing radiation or a flux of holes is a form of E′ center [4]; in the simplest model, the E′ center is formed by interaction of a hole with an oxygen vacancy in the SiO_2 lattice [5]. The excess silicon may result from reducing conditions generated in the BOX during the high-temperature (near 1300°C) anneal step common in SIMOX processing. During this anneal, the BOX is sealed off from a supply of additional oxygen by the top silicon layer [4]. A logical approach to reducing the bulk hole trapping in the SIMOX material was proposed by Hughes, Revesz, and others [6]: to convert the SIMOX BOX into a more nearly stoichiometric SiO_2 layer (presumably, more like a "thermal" oxide) by adding additional oxygen to the BOX after completion of SIMOX processing. The additional oxygen is added by implantation and then the BOX is annealed to promote oxidation of the excess silicon at a temperature (near 1000°C) known to result in oxide layers with low trap densities.

In this work, we examine radiation-generated charge buildup in both single- and multiple-implant SIMOX buried oxides that have received an additional or supplemental oxygen implant and moderate-temperature anneal. We measured the time-dependent response of these materials to short-pulse radiation exposure as a function of buried oxides that have received an additional or supplemental oxygen implant and moderate-temperature anneal. We measured the time-dependent response of these materials to short-pulse radiation exposure as a function of temperature and applied bias, using a fast capacitance-voltage ($C(V_g)$) technique, and analyzed the results using simple models to determine the primary response mechanisms and associated material parameters. The results indicate that the radiation response of the supplemental-oxygen-implant (SUPOX) SIMOX BOX differs substantially from that of the untreated or standard SIMOX. In contrast to standard SIMOX, SUPOX SIMOX shows greatly reduced trapping of radiation-generated holes in the interior (bulk) of the BOX and transport of holes through the BOX similar to that observed in thermal oxides. Also unlike standard SIMOX, and like thermal oxides, the single-implant material shows little or no shallow trapping and subsequent detrapping of electrons in the bulk of the BOX. However, unlike thermal oxides, at least the single-implant SUPOX material shows evidence for substantial long-term, or deep, trapping of radiation-generated electrons in the BOX.

II. Samples and Experimental Techniques

IBIS Technology Corporation supplied two types of supplemental-implant SIMOX in wafer form. The single-implant SUPOX material was produced with a $1.8 \times 10^{18}/cm^2$ 200-keV oxygen implant and subsequent high-temperature anneal; the multiple-implant SUPOX material received three lower-dose oxygen implants with interspersed anneals. Follow-

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ing normal SIMOX processing, each wafer received a supplemental oxygen implant of $1 \times 10^{17}/cm^2$, followed by a 1-hour, 1000°C anneal. Nominal BOX thicknesses for the single- and multiple-implant wafers were 403.4 and 387.3 nm, respectively. BOX metal-oxide semiconductor (MOS) capacitors were fabricated on the SUPOX wafers at the Army Research Laboratory Semiconductor Engineering and Materials Technology Facility (ARL SEMT). These BOXCAPs consisted of n^+-doped superficial-Si and polysilicon electrodes over the BOX layer on the p-type Si substrates. $C(V_g)$ measurements on these units were sensitive to charge effects at the substrate/BOX (back) interface.

We irradiated the BOXCAPs with 4-μs, 13-MeV electron pulses using the Armed Forces Radiobiology Research Institute (AFRRI) electron linear accelerator (LINAC). The samples were exposed under a selectable gate bias, V_g, in an evacuated sample holder with provisions for temperature control from 77 to 450 K and for both active and passive dosimetry (PIN diode, thermoluminescent dosimeters). To minimize perturbations of the internal electric field in the BOX by radiation-generated space charge, the BOX dose was kept below 30 krad(SiO_2) and the magnitude of the electric field, ε_{ox}, applied across the BOX was kept relatively large (near 1 MV/cm for 40 V across 400 nm) [7]. We recorded $C(V_g)$ characteristics for the BOXCAPs before and from 0.2 ms to 800 s after a radiation pulse using a fast measurement system [8] by interrupting the DC gate bias, applying a 160-μs voltage ramp, and simultaneously recording the sample capacitance. Midgap voltage shift as a function of time after irradiation, $\Delta V_{mg}(t)$, was obtained from the $C(V_g)$ data. ΔV_{mg} is assumed to be equivalent to that component, ΔV_{ot}, of the radiation-induced shift in the $C(V_g)$ characteristics caused by oxide trapped charge. The variability in the measured $\Delta V_{mg}(t)$ from curve to curve caused by pulse-to-pulse dose variations, sample variations, and ΔV_{mg} measurement/extraction errors is estimated to be the greater of ±3 V or ±0.1 ΔV_{mg}. Point-to-point error in $\Delta V_{mg}(t)$ within a given curve caused by ΔV_{mg} measurement/extraction errors alone is estimated to be ±1 V.

III. Results

Figure 1 shows $C(V_g)$ curves for a single-implant SUPOX sample irradiated to 26 krad(SiO_2) at 194 K with $V_g = -40$ V. The dashed curve is the preirradiation characteristic; the other curves were taken at the indicated times following the radiation pulse. At 0.2 ms after irradiation, the sample shows a negative shift ($\Delta V_{mg} = -15$ V); this shift recovers with time past the preirradiation value and is positive at 800 s ($\Delta V_{mg} = 8$ V).

Figure 2 shows $\Delta V_{mg}(t)$ for single-implant samples irradiated with $V_g = 40$ V (ε_{ox} near 1 MV/cm) (Fig. 2a) and $V_g = -40$ V (ε_{ox} near −1 MV/cm) (Fig. 2b) at temperatures near 120, 195, and 405 K at an average dose of 26 krad(SiO_2). For V_g = 40 V, the observed shifts are large and negative; for negative bias, the shifts are substantially smaller, and both negative and positive shifts are observed. For the −40-V cases, ΔV_{mg} at early times (near 0.2 ms) is near −15 V at both 120 and 194 K. At 120 K, ΔV_{mg} just begins a slow recovery (becomes less negative) at about 1 s; at 194 K, ΔV_{mg} shows a relatively rapid

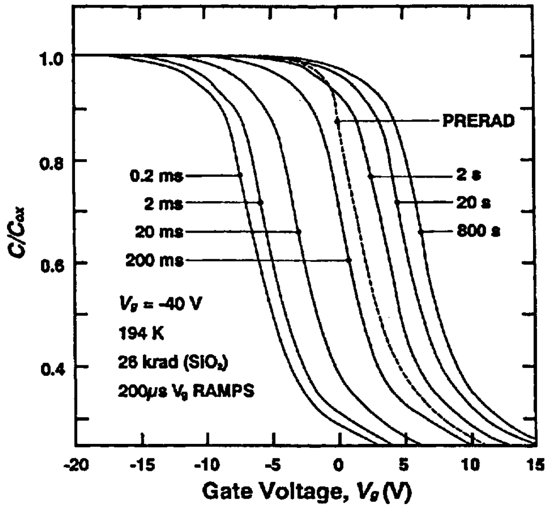

Figure 1. $C(V_g)$ **curves for a single-implant supplemental-oxygen-implant SIMOX BOXCAP before (dashed curve) and after (solid curves) exposure to a 26-krad(SiO_2) LINAC pulse at 194 K with** $V_g = -40$ **V.**

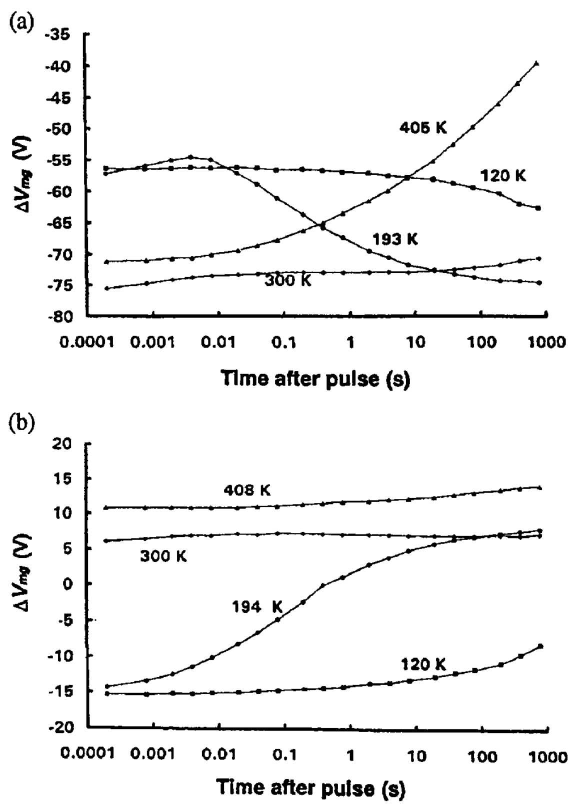

Figure 2. $\Delta V_{mg}(t)$ **for single-implant supplemental-oxygen-implant SIMOX BOXCAPs after exposure to 26-krad(SiO_2) LINAC pulses at various temperatures: (a)** $V_g = 40$ **V and (b)** $V_g = -40$ **V.**

transition to a *positive* 8-V shift at late times (near 800 s). At 300 K, ΔV_{mg} is near 7 V and shows little change with time. Overall, the data suggest a temperature-activated recovery process that is barely begun at 800 s at 120 K and is largely complete by 800 s at 300 K. A similar pattern is observable in the +40-V data (Fig. 2a). In this case, ΔV_{mg} is near –56 V at early times at 120 and 193 K; a rapid transition is made at 193 K to near –75 V, and ΔV_{mg} shows little change (slight positive shift to –71 V) from near –75 V at 300 K. At 405 K, ΔV_{mg} starts out near –71 V at 0.2 ms and then begins a rapid positive shift starting at about 0.01 s. A much weaker positive shift starting at this time is also detectable in the –40-V data at 405 K (Fig. 2b).

Figure 3 shows $\Delta V_{mg}(t)$ measured on triple-implant samples exposed to 14.5-krad(SiO_2) pulses under 40-V (Fig. 3a) and –40-V (Fig. 3b) gate biases. For this material, ΔV_{mg} is always negative for both positive and negative V_g, and shows relatively little change with time (note the expanded ΔV_{mg} scales). Pulse-to-pulse variability in the measured ΔV_{mg} (which primarily affects the positions of the $\Delta V_{mg}(t)$ curves on the voltage scale) makes these data more difficult to interpret. Nevertheless, within experimental error the general pattern of response seen in Figure 2 is discernible here: For V_g = –40 V, the early shift at 121 and 184 K is near –19 V; ΔV_{mg} makes a transition in the positive direction at 184 K to near –15 V and remains there at 294 K. For

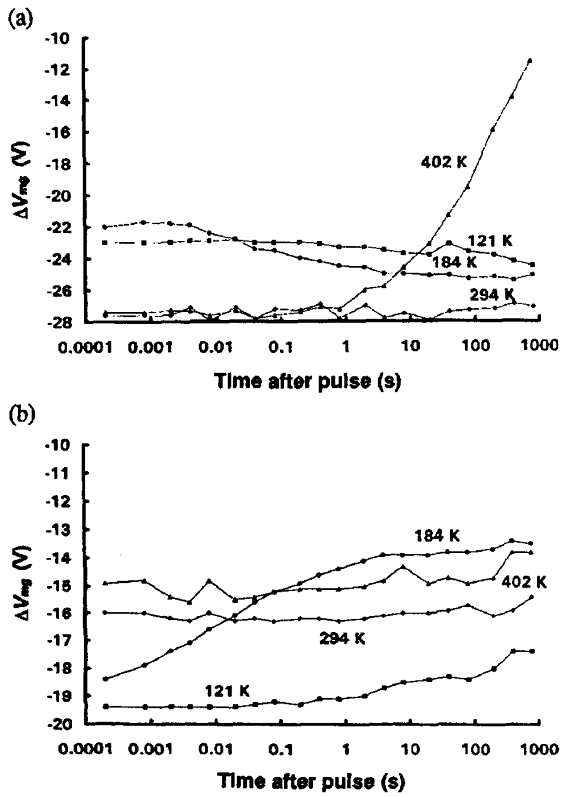

Figure 3. $\Delta V_{mg}(t)$ for triple-implant supplemental-oxygen-implant SIMOX BOXCAPs after exposure to 14.5-krad(SiO_2) LINAC pulses at various temperatures: (a) V_g = 40 V and (b) V_g = –40 V.

V_g = 40 V, the early shifts at 121 and 184 K are near –23 V, and ΔV_{mg} makes a negative-going transition at 184 K. The 294 K and early 402 K shifts are near –28 V; at 402 K, ΔV_{mg} starts a substantial positive recovery at about 0.1 s.

IV. Analysis and Discussion

A. Initial Charge Trapping

As noted in Section III, for the single-implant samples irradiated with V_g = 40 V (Fig. 2a), the shifts at 120 K and at 193 K at early times are near –56 V. These shifts may be compared with ΔV_0, which is the expected ΔV_{ot} for an irradiated oxide layer if all the radiation-generated holes are trapped or immobilized near their points of origin in a uniform distribution through the oxide and no electrons are trapped. These conditions are closely approached in a thermal oxide irradiated below 150 K [9]; at low temperatures, holes are essentially immobile in SiO_2 [5]. For an oxide irradiated with $|\varepsilon_{ox}|$ = 1 MV/cm, $\Delta V_0 = (-1.4 \pm 0.2) \times 10^{-8}\, d_{ox}^2\, D$, where d_{ox} is the oxide thickness in nanometers and D is the high-energy (^{60}Co or LINAC) dose in rads(SiO_2) [9,10]. For the present case, $\Delta V_0 = -59 \pm 9$ V; therefore, within experimental error, the early/low-temperature 40-V shifts are close to ΔV_0. On the other hand, the results for the single-implant samples irradiated under negative V_g (Fig. 2b) show ΔV_{mg} near –15 V at 120 and 193 K at early times, and the shifts become positive at later times and higher temperatures. These results are clear evidence for substantial electron trapping in the single-implant SUPOX BOX. The apparent lack of significant effect of the electron trapping on the positive-V_g low-temperature ΔV_{mg} suggests that any electron trapping is taking place near, or is at least strongly biased toward, the top interface and therefore has little effect on ΔV_{mg}. Reduced effect of electron trapping on ΔV_{mg} under positive V_g would occur even if the electron traps were distributed uniformly through the BOX (see discussion elsewhere [1]).

The early-time 121- and 184-K shifts for the triple-implant SUPOX samples are near –23 V for V_g = 40 V and near –19 V for V_g = –40 V (Fig. 3). ΔV_0 for these samples exposed to 14.5-krad(SiO_2) pulses is -31 ± 5 V. The reduction of the early-time low-temperature shifts well below ΔV_0 for both negative and positive V_g suggests the presence of a substantial density of electrons trapped in the *bulk* of the triple-implant BOX at these times and temperatures. The spatial distribution of the trapped electrons in both the single- and triple-implant materials is examined further in Section IV C, *Modeling of Trapped Charge Distributions.*

B. ΔV_{mg} Recovery Processes

Standard SIMOX BOX contains a high density of shallow electron traps. These traps capture a large fraction of the radiation-generated electrons and then release them by thermal depopulation in about 1 s at room temperature [1]. This process is almost entirely responsible for the time dependence of ΔV_{ot} observed in standard SIMOX BOX structures at times less than a few thousand seconds following irradiation at or below room temperature. At higher temperature and longer times, some positive shift in ΔV_{ot} is observed from thermal detrapping of holes [1]. On the other hand, in thermal oxides, the major cause of time-varying ΔV_{ot} below room temperature for times less than 1000 s after irradiation (early/low-temperature ΔV_{ot} or ΔV_{mg}) is the slow, time-dispersive transport of radiation-generated holes through the oxide [11,5]. Following the hole transport, additional ΔV_{ot} change is caused by removal of holes from traps primarily at the SiO_2/Si interfaces by thermal depopulation and tunneling processes [12,5].

1. Early/Low-Temperature Recovery

Recent measurements using the 10-keV x-ray photoconduction technique show clearly that substantial hole motion takes place in single-implant SUPOX SIMOX BOX layers within 1 s after irradiation at room temperature [13]. (In contrast, no hole motion is observed in standard SIMOX materials [2,13].) Therefore, the candidate processes to describe the time dependence of early/low-temperature ΔV_{mg} in the SUPOX BOX materials are hole transport and electron thermal detrapping. (*Slow* transport of electrons in SiO_2 has not been observed.) For both the single- and triple-implant materials, the early/low-temperature recovery process produces negative-going $\Delta V_{mg}(t)$ under positive V_g and positive-going $\Delta V_{mg}(t)$ under negative V_g (Figs. 2 and 3). The *sign* of the change in ΔV_{mg} with time is no sure clue to the nature of the process: Transport of holes through the oxide can result in negative-going ΔV_{mg} if more than half of the holes are captured by traps at the sensitive SiO_2/Si interface (in the present case, the BOX/substrate interface), and detrapping of electrons in the oxide bulk can cause positive-going ΔV_{mg} if more than half of the detrapped electrons are retrapped at the sensitive interface. However, from the continuous-time random-walk (CTRW) model for hole transport, when $\Delta V_{ot}(t)$ resulting from hole transport is plotted as a function of log(t) (as has been done for our data), a characteristic S-shaped curve results. The shape of this curve is characterized by the parameter α, which determines the time dispersion, or spread, of the $\Delta V_{ot}(t)$ recovery [11,5]. Further, the CTRW model predicts specific behavior for $\Delta V_{ot}(t)$ at the extremes or asymptotes of the S-curve: i.e., at early times when ΔV_{ot} begins to depart from its initial value and at late times as it approaches its final value. For transport under negative bias, the early and late stages of the transport are expected to be of the forms

$$\{1 - [\Delta V(t) - \Delta V_{final}]/[\Delta V_{initial} - \Delta V_{final}]\} \propto t^{\alpha} \quad (1)$$

and

$$\{[\Delta V(t) - \Delta V_{final}]/[\Delta V_{initial} - \Delta V_{final}]\} \propto t^{-\alpha}, \quad (2)$$

respectively [8]. Accordingly, Figure 4 shows −40 V, 194 K data (solid symbols) for the single-implant material for $\Delta V_{final} = 9$ V and $[\Delta V_{initial} - \Delta V_{final}] = -25$ V. From the slopes of fits to the early and late portions of the data on this log-log plot, we obtain trial values of α of 0.33 and 0.31, respectively. The close agreement of these values suggests that the use of the CTRW model to fit the data is appropriate. Further, the average α value of

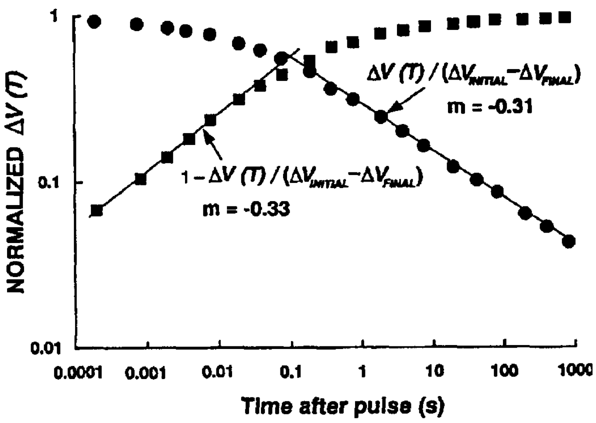

Figure 4. Single-implant supplemental-oxygen-implant SIMOX BOXCAP ΔV_{mg} data from figure 2 for $V_g = -40$ V at 194 K, adjusted and normalized to determine early-time (squares) and late-time (circles) asymptotic behavior.

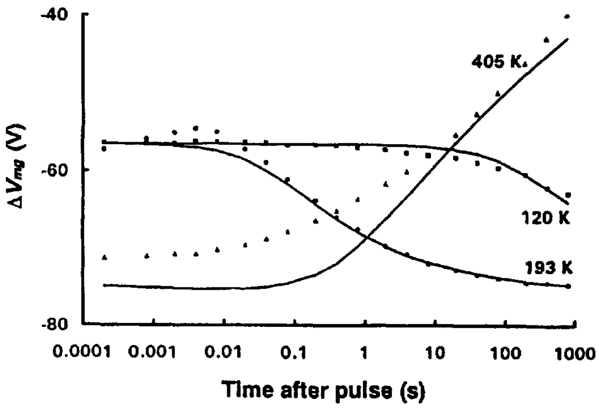

Figure 5. Single-implant supplemental-oxygen-implant SIMOX BOXCAP $\Delta V_{mg}(t)$ data (symbols) from figure 2 for $V_g = -40$ V (ε_{ox} near −1 MV/cm). Solid curves are hole transport and hole annealing model fit (see text).

0.32 is very close to $\alpha = 0.33$ obtained for hole transport in thick thermal field oxides [8]. Therefore, hole transport is the likely ΔV_{mg} recovery process.

The positive-V_g 120, 193, and 405 K data for the single-implant SUPOX material from Figure 2a are replotted in Figure 5 (symbols). Also shown (solid curves) are fits to the data of a general convolution model for the charge response of MOS structures [14]. This model convolves the impulse response functions for hole transport, trapping, and detrapping with a radiation pulse to obtain the overall $\Delta V_{ot}(t)$ of the system. (Interface trap effects may also be added.) For the 120 and 193 K cases, the hole transport was modeled with $\alpha = 0.32$ and an initial shift $\Delta V_{mg}(0^{+}) = -56.5$ V. The time for half of the transport to take place, $t_{1/2}$, was adjusted so that a best fit was obtained to the data at each temperature. Fit values for $t_{1/2}$ were 0.4 s for 193 K and 2000 s for 120 K. The *increasing* negative shift with time in both cases implies that more than half of the holes transporting toward the BOX/substrate interface under the positive gate bias become trapped at or near that interface. The fraction of holes captured at that interface, f_{th}, was also adjusted for the best fit to the 193 K data ($f_{th} = 0.67$).

The greater "noise" and smaller range of recovery seen in the triple-implant results (Fig. 3) preclude fitting the CTRW model to these data. However, as noted in Section III, the time-dependent response is qualitatively similar to that of the single-implant material. Overall, it is reasonable to conclude that hole transport is the dominant early/low-temperature recovery process in both SUPOX materials.

2. Late/High-Temperature Recovery

As noted in Section III, a second recovery process that causes positive-going ΔV_{mg} becomes important in both types of SUPOX material at high temperature (near 400 K) and later times (after 0.1 s). The recovery is most evident in the positive-V_g data for both materials (Figs. 2a and 3a). The process that causes this recovery must be loss of holes from traps at or near the back interface, since the hole transport is already complete and electron motion under positive bias would be directed *away* from the back interface. The delayed onset of the second recovery and its appearance primarily at high temperature suggest that the process is thermal detrapping of the holes near the interface rather than their removal by a tunneling process, since tunneling is only weakly thermally activated and would be expected to begin concurrent with arrival of significant numbers of holes near the interface; i.e., tunneling should overlap the last stages of the hole transport process.

C. Modeling of Trapped Charge Distributions

We employed a simple analytic model developed in previous work [15] to generate estimates of the approximate location and magnitude of charge trapping in the SUPOX BOX materials. The model assumes uniform distributions of electron and hole traps in the oxide layer that capture electrons and holes with mean free paths S_e and S_h, respectively, and traps at the bottom (SiO_2/substrate) interface that capture a specified fraction, f_{eb} or f_{hb}, of the electrons or holes, respectively, that reach that interface. (Trapping at the top interface is not considered here—recall that our measurements are not sensitive to trapping at that interface.) The shifts, ΔV_+ and ΔV_-, under positive and negative bias, respectively, are given by

$$\Delta V_+ = 2\Delta V_0\{S_h[d_{ox}\exp(-d_{ox}/S_h) - S_h(1-\exp(-d_{ox}/S_h))] + S_e[d_{ox} - S_e(1-\exp(-d_{ox}/S_e))] + d_{ox}f_{hb}S_h(1-\exp(-d_{ox}/S_h))\}, \quad (3)$$

$$\Delta V_- = -2\Delta V_0\{S_e[d_{ox}\exp(-d_{ox}/S_e) - S_e(1-\exp(-d_{ox}/S_e))] + S_h[d_{ox} - S_h(1-\exp(-d_{ox}/S_h))] + d_{ox}f_{eb}S_e(1-\exp(-d_{ox}/S_e))\}. \quad (4)$$

Table 1 shows the results of applying the model to selected ΔV_{mg} data for the SUPOX materials and also includes for comparison results from previous work for a standard SIMOX material [1]. The ΔV entries without parameter values (S_e, S_h, f_{hb}, f_{eb}) are the measured values; the ΔV values with entries for the parameters are approximate fits to the measured values reached by trial-and-error adjustment of the parameters. Also shown are other results [2,13] for I_{cm}/I_{co} from x-ray photoconduction measurements performed with 1-s radiation pulses on the standard and single-implant SUPOX materials and the model predictions for these values. $I_{cm}/I_{co} = 1$ corresponds to both holes and electrons moving completely through the BOX within the 1-s measurement time (see discussions elsewhere [2,13]). Results are fit for each material for early time at low temperature (before any hole transport), for 1 s at room temperature (after most of the hole transport and/or shallow electron detrapping), and for late time at high temperature (into the late recovery stage). The model is crude—flat distributions of traps in the oxide bulk and δ-function distributions at the interface—and cannot be expected to produce an exact fit to the results. Nor are the fits obtained necessarily unique. The intent was to determine if the measurement results could be approximately reproduced by reasonable evolution of charge distributions in the BOX.

We fit the standard SIMOX results by adjusting only S_e and S_h (no interfacial trapping) as discussed elsewhere [1]. S_h is much smaller than the BOX thickness d_{ox}, reflecting the very efficient trapping of holes in the BOX bulk; S_e is about 10 times larger. Both S_h and S_e increase with time and temperature, reflecting the thermal detrapping of almost all the electrons and some detrapping of holes.

At low temperature, we fit the single-implant SUPOX results by assuming no hole motion and some bulk trapping of electrons (S_e over six times d_{ox}), together with some trapping of electrons at the back interface. At room temperature, S_h = 1000 nm and $f_{hb} = 0.64$ indicate substantial hole motion and strong trapping of holes at the back interface, in agreement with our results in Section IV. At high temperature, bulk hole trapping is eliminated ($S_h \to \infty$), and the interfacial hole trapping is strongly reduced, reflecting the (probably thermal) hole anneal process. Some electrons are lost from the interface with increasing temperature, but significantly, the bulk electron trapping does not change up to late times at high temperature, indicating that *some electrons are very deeply trapped* in the single-implant material.

Fits to the triple-implant SUPOX data suggest that this material shows more bulk but less interfacial hole trapping than the single-implant material. At low temperature, the results indicate substantial electron trapping (S_e comparable to d_{ox}) but by 1 s at room temperature these electrons are gone ($S_e \to \infty$). This suggests that the triple-implant material has a significant density of shallow electron traps but no deep traps.

V. Conclusions

We have examined the time-dependent response to short-pulse irradiation of single- and triple-implant SIMOX buried oxides that had received a supplemental oxygen implant and anneal. The results show that, in comparison to standard (untreated) SIMOX BOX layers, both types of SUPOX materials show much less trapping of holes in the oxide bulk, as well

Table 1. Bulk-and-interface trapping model results for standard and supplementary-oxygen-implant SIMOX BOXCAPs

SIMOX Material	Dose (krad)	ΔV_+ (V)	ΔV_- (V)	I_{cm}/I_{co}	s_e (nm)	s_h (nm)	f_{hb}	f_{eb}
Standard [1]	9.4	−10.2	−3.2					
137 K, 0.2 ms								
		−10.2	−3.2		202	25	—	—
295 K, 0.8 s		−13.1	−7.1	0.5 ± 0.06 [2]				
		−14.1	−7.2	0.47	600	60	—	—
402 K, 400 s		−12.5	−8.6					
		−14.2	−8.1		3000	150	—	—
Single-implant supplemental O_2	26	−56	−15.3	0.55 [2]				
120 K, 0.2 ms								
		−56	−14.9	0.45	250	0	*	0.35
300 K, 0.8 s		−73	−7.2	0.85 [3]				
		−76	−7.5	0.85	250	100	0.64	0.08
405 K, 400 s		−43	−13.9					
		−42	−13.9		250	∞	0.38	0.07
Triple-implant supplemental O_2	14.5	−23	−19.4					
121 K, 0.2 ms								
		−24	−18.7		500	0	*	0
294 K, 0.8 s		−28	−16.2					
		−28	−16.1		∞	160	0.16	0
402 K, 400 s		−11.5	−13.8					
		−11.6	−6.3		∞	530	0	0

*[1]From ref. [1]; [2]From ref. [2]; [3]From ref. [13]; *"Don't care" values.*

as evidence of hole transport through the oxide similar to that observed in thermally grown oxide layers. Like *soft* thermal oxides (e.g., unhardened field oxides), these materials also show evidence that a large fraction of the radiation-generated holes may become trapped at the SiO_2/Si interfaces and may cause back-channel voltage shifts in excess of those observed for 100-percent bulk hole trapping in standard SIMOX. Annealing of these trapped holes evidently takes place at high temperature by thermal detrapping.

The electron-trapping properties of the single- and triple-implant SUPOX materials differed from those of standard SIMOX and from each other. Unlike the standard SIMOX, the single-implant SUPOX showed substantial *deep* trapping of electrons in the BOX bulk and almost no *shallow* trapping. The triple-implant SUPOX material showed reduced shallow electron trapping in comparison to standard SIMOX, and no deep trapping.

The nature of the electron traps in SIMOX is not clear at this time. The E′ center—long considered to be the primary hole trap—has also recently been identified as a candidate deep electron trapping site [16]. It may also be a shallow electron trap. It is possible that substantial deep electron trapping in standard SIMOX is masked by the extensive deep hole trapping. DC conduction measurements on the SUPOX BOX materials [17] indicate that the triple-implant material has lower conductivity (more like that of a thermal oxide) than does the single-implant material: this in turn suggests that more of the oxygen-deficiency defects have been eliminated. If these defects include the deep electron traps, then the presence of these traps in the single-implant material and their absence in the triple-implant material may be explained. However, this argument does not explain the apparent presence of shallow traps in the triple-implant material.

The reduction of the density of bulk hole traps in the SIMOX BOX brought about by the supplemental-oxygen processing opens the way for hardening of the BOX by techniques developed for reducing or compensating interfacial hole traps in conventional thermal oxides. The creation of deep electron traps in the single-implant supplemental-oxygen material may also be useful for radiation hardening of the buried oxide.

VI. Acknowledgements

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VII. References

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