Determination of the Charge-Trapping Characteristics of Buried Oxides Using a 10-keV X-Ray Source

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Abstract

Oxide photocurrent measurements and capacitance-voltage shift measurements were performed with a 10-keV x-ray source on metal-oxide semiconductor (MOS) buried-oxide (BOX) capacitors to characterize the charge motion and trapping in SIMOX buried-oxide layers. Photocurrents measured in the BOX are about one-half of the expected theoretical current that would be measured if both charge carriers moved through the oxide. Results from the photocurrent measurements together with capacitance-voltage (C-V) measurements and theoretical modeling indicate (for radiation generated charges escaping initial recombination) that holes are essentially trapped in place and most electrons move through the bulk oxide.

Introduction

Silicon-on-insulator (SOI) SIMOX integrated circuit technology has many advantages due to its good isolation characteristics, including reduced dose rate and single-particle response and freedom from latchup. These properties make SOI materials attractive for radiation-hardened microelectronics. However, in order to take full advantage of these attractive features it is necessary to learn more about the radiation-induced effects in the buried-oxide layer. If substantial differences are observed in the radiation response of buried-oxides from that of thermal oxides, different procedures may be required in order to effectively use these materials. While several studies have addressed the total-dose radiation response of various BOX materials [1-3], the nature of the motion and trapping of radiation-generated charge in these materials remains undefined.

The work presented here addresses the issues of the charge transport and trapping properties of the BOX layer. Simple and straightforward experimental techniques using commonly available equipment are used to study the response of the oxide layer when exposed to x-ray radiation. A commercially available 10-keV x-ray source was used to measure the motion of radiation-generated charge using MOS BOX "dot" capacitors in a photocurrent experimental technique described by Benedetto and Boesch [4]. In that work the authors determined the total charge yield in radiation-hardened gate-oxide samples (samples known to show no significant bulk trapping of radiation-generated charge carriers). It is assumed initially that the SIMOX BOX materials will show considerable differences in trapping characteristics from radiation-hardened thermal gate-oxide samples. Here we have used the photocurrent experimental technique as a method to study the trapping characteristics of BOX samples. The same 10-keV x-ray source was also used to obtain information about total dose effects in the BOX by recording pre- and post-irradiation C-V curves and measuring the mid-gap voltage shifts, \( \Delta V_{\text{m}} \). The conduction current measurements yield information on the magnitude of the charge moving through the oxide layer; however, it is insensitive to the sign of the moving charge. Measurements of total-dose-induced \( \Delta V_{\text{m}} \) provide information on the moment of the net charge trapped in the oxide. The results of both the photocurrent measurements and the C-V measurements can be used in theoretical models which provide information about the magnitude and approximate distribution of the radiation-generated charges in the oxide layer.

Therefore, we have developed two relatively easy experimental procedures and analytic tools for characterizing the radiation-generated charge motion and trapping in BOX materials. Additionally, the experiment uses dot capacitor samples which are easily fabricated and well understood. These advantages will allow for quick-turnaround measurements on BOX samples.

Theory

When a MOS device, under bias, is exposed to ionizing radiation, electron-hole pairs are created in the oxide layer. Depending on the electric field in the oxide, some fraction of the charge carriers escape initial recombination. In conventional thermal oxides, most of the electrons escaping recombination are rapidly swept out of the oxide (in picoseconds), while the holes escaping recombination transport slowly to the interface where some fraction are trapped. (This fraction is small in rad-hard thermal oxides.) The generation of charge in the oxide layer depends, in general, on the local electric field, \( E \), and the energy of the ionizing radiation, \( E \). The radiation-generated charge density, \( \rho_e \), given in \( \text{C/cm}^2 \), can be expressed as

\[
\rho_e = |K(E)| f_1(E, E)|R_{\text{DE}}(E, t_m)|D(E),
\]

where \( K(E) \) is the charge generation constant \( \text{(in C/cm}^2\text{rad(SiO}_2)\text{)} \), \( R_{\text{DE}}(E, t_m) \) is the dose enhancement factor, \( D(E) \) is the total dose absorbed in the bulk oxide \( \text{(in rad(SiO}_2)\text{)} \) without correction for dose enhancement, and \( t_m \) is the thickness of the oxide layer in centimeters [4]. The fractional yield, \( f_1(E, E) \) is the field-
dependent fraction of radiation-generated charge escaping recombination and is given empirically by Dozier et al [5]

\[ f_s(E) = \left(1.35/E + 1\right)^{1.69}. \]  

We assume that \( K(E) = K_c(E) f_s(E) \) and \( R_s(E, t) \) for SIMOX buried oxides is the same as for thermal oxides since in the past no statistically significant differences in the constants and quantities have been seen over a wide range of materials [4-6]. So for both oxides irradiated with 10-keV x-rays, \( K_c = 1.38 \times 10^4 \text{ C/cm}^2 \text{ rad(SiO}_2) \) and \( R_s \) was determined from existing data for silicon on SiO\(_2\) [4].

The radiation-generated free electron-hole pairs (the charge carriers) give rise to a conduction current in the oxide layer. If we assume no bulk trapping, or trapping only at the interfaces, then this current is proportional to the MOS capacitor area \( A \), oxide thickness, and the rate of free charge generation, \( \rho_g \), and is given by

\[ I_m = A \int \rho_g(t) \text{d}t = A \int_0^\infty K_c(E)f_s(E)R_s(E,t)D_s(E) \text{d}E. \]  

where \( D_s(E) \) is the bulk-oxide dose rate, in rad(SiO\(_2\))/sec. The results reported here use a photocurrent technique based on measuring the conduction current generated in the oxide.

It is anticipated that the BOX materials will contain charge traps. The current that is actually measured by the photoconduction current experiment is a measure of charge moving through the oxide, which can be affected by trapping in the bulk oxide. (The photocurrent is insensitive to interface trapping.) Charge traps in the BOX will, in turn, reduce the distance the charges travel in the oxide which will reduce the current measured by the experiment. Therefore, due to trapping, the actual photocurrent measured in the BOX, \( I_{ph} \), will be some fraction of the photocurrent given in eq. (3). This fraction, \( I_{ph}/I_m \), contains information about the amount of charge moving in the BOX, and therefore information about the amount of trapping in the bulk oxide. This fraction may also be expressed as:

\[ I_{ph}/I_m = (P_a + P_s)/I_m, \]  

where \( P_a \) and \( P_s \) are the mean drift distances or path lengths that the radiation-generated holes and electrons, respectively, travel through the oxide from their point of creation to an interface. In the absence of trapping in the bulk of the oxide, this path length for a carrier is just half the oxide thickness, \( t_o/2 \). If we assume, for simplicity, that the electrons and holes may each be captured by traps distributed uniformly in the oxide bulk, then it may be shown that the mean free path lengths for the carriers are given by:

\[ P_a = \left( S_a/2\right) \left(1 - 5/4 S_a + 2 S_a \exp(2 - t_o/S_a) - \left(3/4 S_a + t_o/2\right) \exp(-2 t_o/S_a)\right) \]  

\[ P_s = \left( S_s/2\right) \left(1 - 5/4 S_s + 2 S_s \exp(2 - t_o/S_s) - \left(3/4 S_s + t_o/2\right) \exp(-2 t_o/S_s)\right) \]  

where \( S_a \) and \( S_s \) are the mean free paths for capture of the holes and electrons at deep traps. (Note that these trapping lengths, \( S \), are very different from the mean drift distances, \( P \), defined above. In the absence of trapping, \( S \) approaches infinity, while \( P \) approaches \( t_o/2 \)).

### Samples and Experimental Details

The SIMOX BOX samples were supplied by Ibis Corporation and Texas Instruments (TI) Corporation, and the thermally grown, radiation-hardened gate-oxide sample was fabricated by Hughes Aircraft Corporation (HAC). TI and Ibis supplied the SIMOX wafers only, and electrode deposition and packaging of the BOX capacitors were done at the Harry Diamond Laboratories (HDL) Microelectronics Facility. The Ibis BOX samples were nominal 20- or 30-mil diameter dot capacitors with an Al electrode and a BOX thickness of approximately 260 nm. The top Si layer was chemically etched away on these samples, and an Al electrode was deposited directly on the buried SiO\(_2\) layer. The TI BOX samples were nominally 18- x 18-mil square capacitors with a square Al electrode placed on the top Si layer and oxide thickness of approximately 432 nm. The TI samples had guard rings around the top electrodes to eliminate surface leakage paths. The HAC sample was a nominal 25-mil diameter dot Al-gate capacitor with an oxide thickness of about 39 nm.

Room temperature photoconduction current measurements were taken using an ARACOR model 4100 10-keV x-ray machine. The samples were placed in a vacuum chamber to eliminate air ionization currents, and a bias was applied to the sample substrate. The guard rings were grounded. A lead collimator was placed above the sample to insure that only the active area of the sample was irradiated, and thereby minimize any stray currents. Upon irradiation, the x-ray-generated current from the buried oxide was measured between the top electrode and ground using a Keithley model 462 picoammeter. Irradiation and measurement time was on the order of a second, which at room temperature makes it impossible to see fast electron trapping and de-trapping. A schematic of the experimental setup used to perform these measurements is shown in Figure 1. More explicit details on this experimental technique can be found in Benedetto and Boesch [4].

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**Figure 1.** Schematic diagram showing experimental apparatus used to take photoconduction current measurements.
All measurements were taken with the x-ray machine operating at an accelerating potential of 60 kV. The total dose was kept low to avoid perturbation of the oxide electric field by space charge buildup. Samples were irradiated under oxide fields from about 0.1 MV/cm up to fields where they began to break down (fields of about 3, 4, and 5 MV/cm for TI, Ibis, and HAC samples, respectively).

The same 10-keV x-ray source was used to irradiate the samples in order to measure $\Delta V_{gm}$ in the BOX capacitor. The midgap voltage shift was found by taking pre- and post-irradiation C-V measurements. C-V measurements were made by applying a voltage ramp to the sample substrate and ground, and monitoring the sample capacitance with a Boonton capacitance meter connected to the top electrode and ground.

Results

Figure 2 shows a typical set of raw data obtained from the photocurrent measurements. Here the x-ray generated conduction current is plotted versus the oxide field for four BOX samples. As a standard of comparison for the charge motion in the BOX samples, the photocurrent in an HAC radiation-hardened gate-oxide capacitor is also shown, since these samples are known to exhibit no measurable bulk trapping. As expected, in each case the conduction current increases with increasing oxide field. It is important to note that Figure 2 plots the total conduction currents which are dependent on sample area and thickness, and constants pertaining to the radiation source, including charge yield, dose rate, and dose enhancement factor.

The dose enhancement factor is a function of the thickness of the oxide and the energy of the ionizing radiation. Since all samples have been irradiated with the same source operating at the same energy in this study, the dose enhancement factor is dependent on oxide thickness only, $R_{enh} (E, t_o) = R_{enh} (t_o)$. Based on the data from Benedetto and Boesch [4], $R_{enh}$ was taken to be 1.2, 1.4, and 1.56 for TI, Ibis, and HAC samples, respectively.

In Figure 3 we plot the measured photocurrent $I_{ph}$ normalized to the theoretical maximum current $I_{th}$ as a function of oxide field $E_{ox}$. As expected, this quantity for the radiation-hardened gate-oxide capacitor is about unity for fields above 0.3 MV/cm. (The slightly higher values at lower fields arise from uncertainties in the measurements and in the empirical formula for $f$ as given in Dozier et al [5].) This is because both charges move through the oxide and are either collected at the electrode or are trapped at the interface. Note that for each of the BOX samples $I_{ph}/I_{th}$ is about the same, despite the differences in processing, capacitor area, oxide thickness, and dose rate. Of even greater importance, observe for any given field the measured current in the BOX is about half of the theoretical maximum value.
C-V measurements were performed on two identical TI samples, one irradiated under positive and the other under negative bias, corresponding to an oxide field of ±1 MV/cm. Shown in Figure 4 are the C-V curves taken before and after irradiation. Mid-gap voltage shifts were measured as ΔV_{mg} = -6.4 V and ΔV_{mp} = -4.4 V for positive and negative biases, respectively. An Si p-i-n diode was used in measuring the total dose as 2.7 krad(SiO₂). Correcting for dose enhancement, the total dose absorbed in the oxide is 3.24 krad(SiO₂). The fact that ΔV_{mp} is negative and of fairly similar magnitude for both positive and negative bias is indicative of a net positive charge contained primarily within the bulk of the oxide. The relatively slight difference in the magnitude of ΔV_{mg} in the two cases can be attributed to the hole distribution being skewed toward one interface or the other (depending on bias) and possibly some electron trapping.

![Figure 4. Pre- and post-irradiation capacitance-voltage curves showing the mid-gap voltage shifts for samples irradiated under ± 1 MV/cm.](image)

If we were to assume (for the radiation-generated charges escaping recombination) that one charge carrier (holes) is completely trapped in place (S₀ → 0), while the other (electrons) moves completely through the oxide (S₁ → ∞), the mid-gap voltage shift is expected to be a maximum and given by [7]

\[
\Delta V_{mg}^\text{max} = -1.9 \times 10^6 f_0 (E_{ox}) t_{ox}^2 D.
\]

For BOX capacitors irradiated to a total dose of D = 3.24 krad(SiO₂) with an applied field of E_{ox} ± 1 MV/cm, the expected values are ΔV_{mg}^\text{max} = -5.3 V. Recall from Figure 4 we measured a ΔV_{mp} = -6.4 V and ΔV_{mp} = -4.4 V. Within our overall experimental error (including dosimetry and dose enhancement), these values are reasonably close to ΔV_{mg}^\text{max}. This implies, as assumed, that most holes are being trapped in the oxide while most electrons are moving out of the oxide. The fact that L_{rug}^\text{max} is so close to 0.5 lends weight to the conclusion that, in fact, the holes are trapped almost in place and the electrons move completely through the oxide.

The results for L_{rug}/L_{so} as a function of E_{ox} for the BOX samples are replotted in Figure 3b on an expanded scale. While the results show scatter on this scale, some evidence of a definite dependence of L_{rug}/L_{so} on field can be seen. L_{rug}/L_{so} increases significantly for each sample above 0.5 MV/cm. This may reflect a slight increase in S₀ or a large increase in S₁, probably due to a decrease in trap cross section as a function of oxide field. If we assume that the hole trap cross section varies as E_{ox}^{-1/2} as has been seen in thermal oxides [8], then the observed L_{rug}/L_{so} dependence on E_{ox} may be explained by a decrease in S₀ from 48 nm at 4 MV/cm to 20 nm at 0.7 MV/cm in the Ibis samples, and a similar decrease in the TI samples.

**Conclusions**

Photoconduction current measurements have been performed on SIMOX BOX materials in order to determine the nature of the charge trapping and transport characteristics of the BOX layer. Measurements have been performed on MOS capacitors using fairly simple and straightforward experimental techniques with commercially available equipment. The photocurrent measurements together with C-V shift measurements indicate that the holes are essentially trapped in place and that most of the electrons move completely through the oxide. The experimental data have been modeled yielding results which support these conclusions. These results clearly indicate that the radiation response in the BOX is quite different from that of a rad-hard gate oxide, and that new and different techniques will be necessary in order to harden these materials.

As noted earlier, if the BOX were behaving like the radiation-hardened oxides and all the charge was to move through the oxide, the measured photocurrent in the BOX would be the same as that in the rad-hard samples; i.e., we would measure L_{rug}/L_{so} = 1. On the other hand, if one charge is completely trapped at its point of origin while the other moves completely out of the oxide, a fraction of one-half would be obtained, L_{rug}/L_{so} = 0.5. As shown in Figure 3a, we actually measure L_{rug}/L_{so} = 0.5 ± 0.06 at all fields for all four BOX samples. While various combinations of S₀ and S₁ can yield L_{rug}/L_{so} = 0.5, this result clearly suggests it is likely we may have the case of one freely moving carrier and one strongly trapped carrier.

As we have also noted, the photoconduction current measurements provide information on the magnitude but not the sign of the moving charge. In order to determine which carrier is predominately moving and which is predominately trapped, we turn to our C-V measurements which were used to measure ΔV_{mg}.
Acknowledgments
The authors would like to thank the people at the HDL Microelectronics Facility involved with sample preparation, Barry McLean, Tim Oldham, and Jim McGarrity for useful discussion, Aivars Lelis for help with anything involving computers, and Sherry Scheckels for manuscript preparation.

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