INTERFACE-STATE GENERATION IN RADIATION-HARD OXIDES*

P. S. Winokur and H. E. Boesch, Jr.

U. S. Army Electronics Research and Development Command
 Harry Diamond Laboratories
 Adelphi, Maryland 20783

Abstract

Results of several experiments are presented to demonstrate that there is a time-dependent buildup of interface states in hardened dry oxides following pulsed LINAC irradiation and to establish the field and dose dependencies of the interface-state buildup in these dry oxides. These results suggest that the same mechanisms are responsible for the interface-state buildup in both wet-grown and dry-grown oxide capacitors, the major difference being that the magnitude of the buildup in a hardened dry oxide is considerably smaller than that in a hardened wet oxide. For several lots of wet-grown and dry-grown oxide capacitors no increase in interface states was observed following exposure to a neutron fluence of $\sim 10^{13}$ n/cm².

Introduction

Radiation-induced interface states in SiO₂/Si MOS systems continue to be an important and active area of research in the electronics industry and radiation-effects community. As part of our program to develop a model for the buildup of radiation-induced interface states, our group has performed detailed characterizations of interface-state buildup in hardened wet-grown and soft dry-grown oxide capacitors. In prior studies,^{1,2} we have reported a time-dependent buildup of interface states and have characterized the buildup's dependence on field, dose, and temperature. In summary, we found that the buildup of interface states in wet-oxide MOS capacitors under positive bias is a two-stage process. The first stage, which occurs during the time required for holes to transport to the SiO₂/Si interface, determines the final or saturation value of interface states and was found to be field dependent and temperature independent. The second stage, which begins after the holes have reached the SiO₂/Si interface and continues for several thousand seconds, determines the time scale for the buildup and was found to be both field and temperature dependent.

Although we have observed and reported on a time-dependent buildup of interface states in wet-oxide and soft dry-oxide capacitors, until recently we had not observed a time-dependent buildup of interface states in a hardened dry oxide following pulsed LINAC irradiation. The question arose as to whether the generation of interface states in a hardened dry oxide was instantaneous with the radiation pulse, or whether the experimental procedures we had used in the past were not sufficiently sensitive to detect a time-dependent buildup of interface states. Possible experimental difficulties arise from the very nature of making a time-dependent measurement of interface states at room temperature, where it is necessary to deliver an adequate dose to the sample to produce observable changes in ΔN_{ss} in less than 1 s, while avoiding problems of space charge and heating. Specifically, for the hardened dry oxide at room temperature this is not possible since the dose required to produce clearly observable ΔN_{ss} is ~ 5 Mrad (considerably higher than in wet

and soft dry oxides) and this dose cannot be delivered at the LINAC in short times without incurring problems of space charge and heating.¹

In this paper we present a detailed characterization of the interface-state buildup in a hardened dry oxide. The results of several experiments will be presented to (1) show that there is indeed a time-dependent buildup of interface states in hardened dry oxides following pulsed LINAC irradiation, and (2) establish the field and dose dependencies of the interface-state buildup in these dry oxides. We also present results of neutron irradiations on the same MOS capacitors reported on by Srour et al.³ in which they proposed the existence of neutron-induced interface states to explain a neutron-induced change in surface recombination velocity.

Samples and Experimental Approach

The "hardened"⁴ MOS capacitors used in these experiments were supplied by Hughes Aircraft Corporation and consisted of dry-grown SiO₂ layers on <100> n-type silicon substrates with carbon-crucible-source vapor-deposited Al gate electrodes. The dry oxide was thermally grown at 1000°C to a 910-Å thickness and was not annealed.

The pulsed irradiation experiments were performed using the electron linear accelerator (LINAC) at the Armed Forces Radiobiology Research Institute. The LINAC produces a nominal 13-MeV 1-A electron beam with a pulse width of 4 μ s and a typical dose of 50 to 200 krad(SiO₂) per pulse depending on LINAC-to-sample geometry. Steady-state ⁶⁰Co irradiations were performed using a 20-kCi (~ 600 rad(Si)/s) source at the Harry Diamond Laboratories. High-frequency 1-MHz capacitance-voltage (C-V) traces were taken at 77 and 295 K before and after pulsed or steady-state irradiations. The room temperature C-V traces were digitized and analyzed by the Terman technique. The resulting distributions of interface states were integrated over a portion of the Si band gap from 0.3 eV below to 0.3 eV above mid-gap to provide single values, N_{ss} (cm⁻²), of interface states in the sample as functions of experimental parameters. The 77-K C-V traces were analyzed to determine N_{ss} (cm⁻²) in the mid 0.7 eV of the Si band gap by using the Jenq technique (see discussion immediately below); the traces were also analyzed for the presence of lateral nonuniformities.⁵ For the samples used in this work, lateral charge nonuniformities were found to be small.

A new experimental approach was employed to observe a time-dependent buildup of interface states in a hardened dry oxide. The new approach used a technique developed by Jenq⁶ for measuring interface states at liquid nitrogen temperature (77 K). The Jenq technique is illustrated in Fig. 1, where a set of C-V traces measured at 77 K (curves 1 and 2) is shown along with a ideal deep-depletion curve calculated at 77 K (curve 3). In this technique a sample at room temperature is biased into accumulation to charge acceptor states in the Si band gap while its temperature is lowered to 77 K. A C-V trace is then taken by sweeping the bias from accumulation into deep depletion in the dark (curve 1). The sample is held in deep depletion (point A) and

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illuminated with visible light to generate minority carriers and charge donor states (point B). A C-V trace is then taken by sweeping the bias from inversion into accumulation in the dark (curve 2). The voltage shift, ΔV , between the lower part of curves 1 and 2 in the region where they are parallel to the ideal deep-depletion curve is a measure of N_{ss} (cm^{-2}) for those interface states which are 0.21 eV away from both the conduction and valence band, i.e., in the mid 0.7 eV of the Si band gap. It was assumed that electrons and holes in these states have emission time constants sufficiently long (>10 s) that they are essentially frozen in these states during the time period required for taking C-V traces.

Fig. 1. Jenq technique for measuring interface states at 77 K. The voltage shift, ΔV , between two 77 K C-V traces is a measure of the integrated interface-state density over the mid 0.7 eV of the Si band gap, i.e., $N_{ss} = \Delta V \epsilon_{ox} / (q d_{ox})$, where ϵ_{ox} , d_{ox} , and C_{ox} are the oxide dielectric permittivity, thickness, and capacitance, respectively, and q is the electronic charge.

In the experiment discussed in this paper, C-V traces were initially recorded at 295 and 77 K in order to calculate the preirradiation value of interface states by using the Terman and Jenq techniques, respectively. In order to produce observable changes in ΔN_{ss} while avoiding problems of space charge and heating, the sample was then irradiated at the LINAC to a dose of 20 Mrad (SiO_2) at 77 K and with an applied field of 5 MV/cm. The advantage of irradiating at high field and low temperature is that at 77 K, radiation-generated holes still transport fairly rapidly through the oxide,⁷ but the strongly temperature activated interface-state buildup is inhibited.^{1,2,6} As shown in previous work,² transport of the holes through the oxide is a necessary first stage for the buildup of radiation-induced interface states. In addition, because the rate of buildup of interface states is strongly temperature-activated, interface states are not observed to build up on any reasonable time scale at 77 K. Consequently, we were able to deliver the 20-Mrad dose to the sample over a 15-minute period, thereby avoiding sample heating and unacceptable space charge buildup in the oxide. During irradiation, and for ~20 min following irradiation, the 5-MV/cm field was maintained across the oxide. At this time, a set of 77-K C-V traces was recorded and analyzed by using the Jenq technique to verify that (1) most of the holes had transported through the oxide and (2) there was no increase in interface states.

Owing to the strong temperature dependence of the interface-state buildup, it was then necessary to raise the sample temperature to observe a buildup. The temperature was raised in ~20 min to 295 K at a reduced field of 0.5 MV/cm. The reduced field is used to slow down any buildup during the warmup. (It had been previously established for wet-grown and soft dry-grown oxide capacitors that the rate of the interface-state buildup is strongly field dependent, with the rate decreasing as the applied field is decreased.²) Once the sample was at room temperature, the field was abruptly switched to 5 MV/cm and C-V traces were generated periodically out to 2000 s (after the bias switch) in order to observe any time-dependent N_{ss} buildup. Finally, at 2000 s, a set of 77-K traces was taken in order to obtain the saturation value of interface states.

Experimental Results and Discussion

In Fig. 2 preirradiation C-V traces are shown on the right side; these include a room temperature C-V trace and two 77-K C-V traces. Using the Jenq technique, we found that the voltage shift between the two 77-K C-V traces is ~0.25 V and corresponds to an N_{ss} of $\sim 6 \times 10^{10} \text{ cm}^{-2}$. The 77-K C-V traces at the extreme left of the figure were taken ~20 minutes after a 20 Mrad (SiO_2) LINAC irradiation and show a net negative shift, with no increase in distortion, resulting primarily from positive charge in the oxide. In addition, analyzing these traces using the Jenq technique reveals essentially the same ΔV (~0.3 V) and therefore no change in interface-state density from the preirradiation 77-K traces. Following warmup (see previous section), the first room temperature C-V trace, taken at 20 s, has the same shape as the preirradiation room-temperature trace, indicating no change in interface states. At later times there is a noticeable increase in distortion of the traces corresponding to the buildup of interface states. At 2000 s, a set of 77-K C-V traces was taken in order to apply the Jenq technique. The analysis yielded an N_{ss} of $3.6 \times 10^{11} \text{ cm}^{-2}$, a six-fold increase over the preirradiation value. This experiment clearly demonstrates the time dependence of the interface-state buildup in a hardened dry oxide following pulsed LINAC irradiation.

Fig. 2. Time dependence of the interface-state buildup in a hardened dry-grown oxide.

Figure 3 shows the increase in interface states, ΔN_{ss} (cm^{-2}), for hardened dry-oxide capacitors following steady-state ^{60}Co irradiation at doses from 10^5 to

2×10^7 rad(SiO_2). Previous results for hard wet-oxide samples are also shown.¹ The results for hardened wet and dry oxides (at fields of 1 and 4 MV/cm) are fit by parallel straight lines over the full range of dose, and in both cases ΔN_{ss} follows a power law dependence on dose with an exponent of 0.65 (approximately 2/3). Also included in this figure is the dose dependence for two additional lots of samples designated HK10 and SA17; HK10 is a wet-grown oxide supplied by Hughes Aircraft Corporation and SA17 is a dry-grown oxide supplied by Sandia Labs. ΔN_{ss} in these oxides also follows a $D^{2/3}$ dependence, suggesting that this dose dependence is universal in nature, independent of oxide type (wet or dry) and applied field.

Fig. 3. Increase in integrated interface-state density, ΔN_{ss} (cm^{-2}), versus ^{60}Co total dose for wet-grown and dry-grown oxide capacitors. ΔN_{ss} was determined by integrating the interface-state density over a portion of the Si band gap 0.3 eV on either side of midgap, except for sample lot HK10 where the integration was from midgap to 0.3 eV above midgap.

Figure 4 shows N_{ss} for the hardened dry oxide at late times following a 5-Mrad(SiO_2) ^{60}Co irradiation plotted versus fields applied across the oxide of -4 to +4 MV/cm. We can see a strong interface-state buildup with increasing positive field and essentially no interface-state buildup at negative fields. These results for the hardened dry oxide are qualitatively similar to previous results for hardened wet-grown oxides (following LINAC irradiation),¹ which are shown in the insert to Fig. 4 (Ref. 1). The strong dependence of the interface-state buildup on field for wet-grown and dry-grown oxides following ^{60}Co irradiation is also evident in Fig. 3, where the buildup is shown at fields of 1 and 4 MV/cm. The functional dependence

of the interface-state buildup on field was independent of the source of ionizing radiation (LINAC or ^{60}Co).

Fig. 4. Integrated interface-state density for a hardened dry-grown oxide versus applied electric field following a 5-Mrad ^{60}Co irradiation.

In summary, we have found for the hardened dry oxide under investigation: (1) a time-dependent buildup of interface states following pulsed LINAC irradiation (Fig. 2) as was previously reported for hardened wet oxides,^{2,3} (2) the same 2/3 power law dependence of interface states on dose (Fig. 3) as was previously reported for hardened wet oxides, and (3) the same qualitative dependence of interface states on applied field (Fig. 4) as was previously reported for hardened wet oxides.¹ These results suggest that the same mechanisms are responsible for the interface-state buildup in both wet-grown and dry-grown oxide capacitors, the major difference being that the buildup in the hardened dry oxide is much smaller than that in the hardened wet oxide. This difference may be attributable to the amount of water incorporated into the oxide during growth and supports earlier conjectures⁸⁻¹¹ that weak Si-H or Si-OH bonds play a major role in radiation-induced interface-state buildup.

A Note on Neutron Irradiation of MOS Capacitors

Last year at this conference Srour et al.³ presented results of measurements of surface recombination velocities in the depletion regions of several different types of MOS capacitors exposed to neutron fluence levels up to 10^{13} n/cm². These MOS capacitors included wet oxides designated KA-09, WET N, and WET P, and dry oxides designated DRY N and DRY P. They observed a one- to two-order-of-magnitude increase in surface recombination velocity in these capacitors at a neutron

level of 10^{13} n/cm² and interpreted these results as evidence of neutron-induced interface states in MOS devices. If this measured neutron-induced change in surface recombination velocity is proportional to a change in interface-state density as Srour et al contend,³ one would expect a large and measurable increase in the interface-state density that should be readily detectable in C-V traces taken following exposure.

We performed neutron bombardment experiments at a fluence level of 1.3×10^{13} n/cm² using a bare critical assembly at the Army Pulsed Reactor Facility on the same sample lots used by Srour et al. The reactor had a gamma-to-neutron ratio of 2.21×10^{-10} rad(Si)/n/cm², and sulfur dosimeters were used to determine the fluence level for a given exposure. Each sample lot was irradiated with an applied field of 0 and ± 2 MV/cm. We measured C-V traces before and after irradiation and observed no shift or increase in distortion of the traces. Our measurements clearly show that the increase in surface recombination velocity reported by Srour et al was not due to an increase in interface states at the SiO₂/Si interface, but probably to neutron-induced damage in the Si depletion region.

References

1. P. S. Winokur, H. E. Boesch, Jr., J. M. McGarrity, and F. B. McLean, IEEE Trans. Nucl. Sci. NS-24, 2113 (1977).
2. P. S. Winokur, H. E. Boesch, Jr., J. M. McGarrity, and F. B. McLean, J. Appl. Phys. 50, 3492 (1979).
3. J. R. Srour, S. C. Chen, S. Othmer, and R. A. Hartmann, IEEE Trans. Nucl. Sci. NS-26, 4784 (1979).
4. A "hardened" oxide is one that has received special processing to achieve tolerance to radiation in the Megarad range. This is generally accomplished either by minimizing the effects of hole trapping and interface states or by compensating the effects of hole trapping with interface states.
5. C. C. Chang and W. C. Johnson, IEEE Trans. Elec. Dev. ED-24, 1249 (1977).
6. C. S. Jenq, Ph.D. Dissertation, Princeton University, (1977).
7. F. B. McLean, H. E. Boesch, Jr., and J. M. McGarrity, Proc. of Intl. Conf. on Phys. of SiO₂ and Its Interfaces (Pergamon, New York, 1978), p. 19.
8. A. G. Revesz, IEEE Trans. Nucl. Sci. NS-24, 2102 (1977).
9. C. T. Sah, IEEE Trans. Nucl. Sci. NS-23, 1563 (1976).
10. K. O. Jeppson and C. M. Svensson, J. Appl. Phys. 48, 2004 (1977).
11. C. M. Svensson, Proc. of Intl. Conf. on Phys. of SiO₂ and Its Interfaces (Pergamon, New York, 1978), p. 328.