GENERATION OF INTERFACE STATES BY IONIZING RADIATION IN VERY THIN MOS OXIDES

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ABSTRACT

The creation of interface states D_{it} by ionizing radiation is investigated in MOS capacitors as a function of oxide thickness in the range 6-50 nm. A comparison of the thickness dependence in etchback and as-grown oxides supports the idea that the number of defects at the $Si-SiO_2$ interface increases with oxidation time. For relatively thin oxides (t_{ox}<12 nm), the rate of increase in D_{it} is significantly smaller than would be extrapolated from the behavior of thicker oxides for both oxide types. This effect is probably caused by tunneling of trapped holes near the oxide interfaces.

INTRODUCTION

The generation of fast interface states D_{it} at the $Si-SiO_2$ interface by ionizing radiation [1-6] and by other processes [7-9] has been investigated extensively because of its importance in the degradation of MOS devices. In the case of ionizing radiation, the number of interface states produced has been found to depend on oxide type (wet or dry), thickness, growth temperature, post-metalization anneal temperature and ambient, gate bias and temperature during irradiation, and even device geometry [10,11]. In this paper, we report on an electrical study of the dependence on oxide thickness where we have attempted to minimize and control the influence of factors besides thickness.

Previous studies have shown that the increase in D_{it} in irradiated MOS samples is larger for thicker oxides [3-5], with reported dependencies varying from $t_{ox}^{2/3}$ [3] to t_{ox}^{2} [4]. To aid in understanding and resolving these variations, we have taken several steps to isolate the oxide thickness contribution. The primary such step, following the technique employed by Hughes [12] and Derbenwick and Gregory [13] in studies of radiation-induced flatband shifts, compares measurements from two oxide types: (1) "as-grown" oxides obtained by varying the oxidation time, and "etchback" oxides where the oxides are all grown to the same original thickness and then chemically etched back. Using this technique, Derbenwick and Gregory [13] deduced that properties of the $Si-SiO_2$ interface change with oxide thickness in as-grown oxides but not in the etchback oxides. In this work, we have observed similar behavior for D_{it} formation.

A second experimental step taken to help isolate the oxide thickness dependence of interface state formation was to adjust the gate bias for samples with different t_{ox} to obtain the same oxide electric field during irradiation (± 2.0 MV/cm) in all samples. This is important because charge transport in the oxide and other processes related to D_{it} generation can depend on the sign and magnitude of the oxide field. This step was not taken in several of the previous studies [4,5].

Since thin oxides must be irradiated to much higher doses than thick oxides to obtain measurable increases in D_{it}, the dose dependence of D_{it} formation must be clearly understood. Previous measurements of the radiation-induced increase in D_{it} have reported a sublinear $dose^{2/3}$ dependence [4,14]. Here, we find D_{it} to increase linearly with dose initially, followed by sublinear dependence at higher doses, implying that the $dose^{2/3}$ dependence is a high dose effect as suggested by McLean [14]. In order to compare oxides of varying thickness, all data reported here is obtained in the relatively low dose linear regime.

Finally, we report one new effect: D_{it} generation in extremely thin oxides (t_{ox}<12 nm) is much smaller than would be predicted based on extrapolation of results from thicker oxides. This qualitatively agrees with previous data showing that the increase in fixed oxide charge in very thin irradiated oxides is also much smaller than expected [4,15-19]. These results suggest that sub-12 nm oxides will be attractive for future hardened VLSI technology.

SAMPLE FABRICATION AND MEASUREMENT TECHNIQUES

MOS capacitors were fabricated on <100> n-type silicon wafers with 5 ohm-cm (as-grown oxides) or 0.5 ohm-cm (etchback oxides) resistivity. Dry oxides were grown in O_2 at 900°C using a polysilicon tube furnace precleaned with HCl. All samples were post-oxidation annealed for 30 minutes in N_2 at 900°C. Oxide thicknesses in the range 6-47 nm were obtained either by varying the oxide growth time ("as-grown" oxides) or by chemically etching oxides grown to the same (47 nm) original thickness in dilute HF. The variation of oxide thickness across the 2 inch wafers was less than 5%. Phosphorus-doped polysilicon was deposited and plasma etched to form the gate metal. Following aluminum metalization, the samples received a final post-metalization anneal in H_2 for 1 hour at 400°C.

The etchback and as-grown oxide samples were fabricated in two different process lots about 6 months apart. The processing of these two lots was kept as similar as possible to allow comparison of radiation results between lots. As will be seen later, this attempt was not successful. No attempt was made to fabricate "radiation-hardened" oxides. All samples in a given lot were processed together such that, insofar as possible, the only difference among samples is their oxide thickness.

Oxide thicknesses were obtained from 1 kHz C-V measurements in strong accumulation and were in good agreement with ellipsometer measurements. Pre-irradiation electrical characteristics of the MOS capacitors were excellent with less than 0.1 pA dc leakage, low initial fixed oxide charge, no measurable mobile ionic charge (using 250°C stress measurements) and low initial D_{it} (typically 5 x 10^9 states/cm^2-eV).

The capacitors were irradiated at the NRL Co^{60} source at room temperature at 0.4 Mrad(Si)/hr while held at constant gate voltage. To minimize the effects of slow time-dependent increases in D_{it}, the gate bias was maintained for 15 minutes following irradiation so that much of the post-irradiation annealing occurs at the same oxide field. Nevertheless, significant slow post-irradiation increases in D_{it} were observed (typically, a 25% increase after an additional 24 hours). Typically, these irradiations and associated post-irradiation measurements were performed on each sample in about 8 hours.

EXPERIMENTAL RESULTS

A. Measurement of D_{it} (Ac Conductance)

D_{it} was measured using the simplified ac conductance technique of Brews [20] at a frequency of 1 kHz. This technique measures D_{it} at a single energy which, at 1 kHz, is close to midgap. An example of ac capacitance and conductance data on a typical etchback sample

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is shown in Fig. 1. Due to the thinness of the oxide (7.6 nm), the C-V shift is only about -5 mV, which is too small to be seen. However, the increase in D_{it} is readily observed as increased ac conductance. The occurrence of two overlapping conductance peaks (see below) causes difficulties because the Brews technique uses the width of the peak to determine σ_s (a measure of the surface potential fluctuations at the Si-SiO_2 interface) which is required to find D_{it}. Consequently, σ_s was determined from the single-peaked pre-irradiation data and then the same value for the post-irradiation data was assumed (σ_s values are in the range 1.1-1.8). This approximation would lead to significant errors as the radiation-induced fixed charge accumulates, causing σ_s to increase. However, we believe the approximation to be valid because σ_s was calculated from the width of a single side of the conductance peak, and only negligible increases in σ_s were observed at low doses. Finally, the accuracy of these ac conductance measurements was compared with low-frequency (similar to quasistatic) data [21] at 77.6°C in two irradiated samples. D_{it} values were in good agreement with <12% differences.

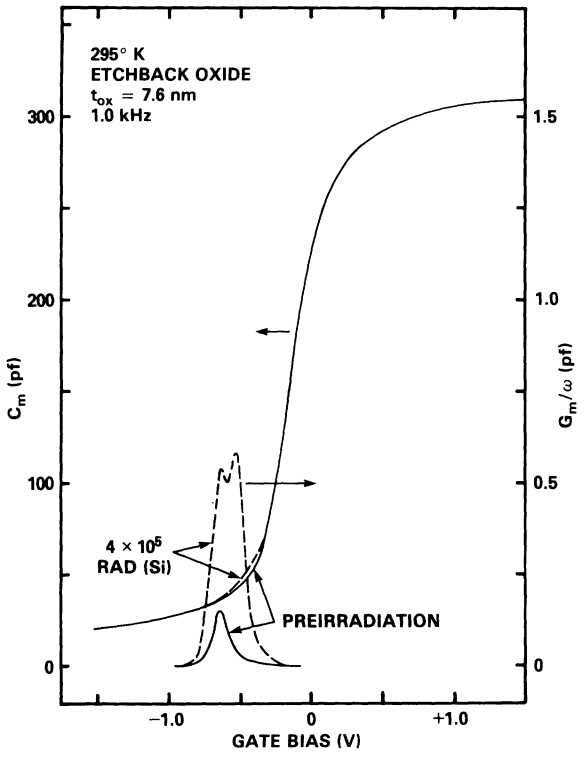

Fig. 1. Comparison of pre-and post-irradiation ac capacitance and conductance data on a 7.6 nm etchback oxide. Double peaked conductance after irradiation suggests two distinct D_{it} levels are formed.

In the ac conductance data (Fig. 1), two close conductance peaks are always observed post-irradiation for thin oxides with t_{ox}<30 nm. In thicker oxides, the two conductance peaks usually could not be separately resolved, but their occurrence could often be inferred from the shape (i.e., distortion) of the conductance data. Also, the two peaks have different creation rates (the right-hand peak increases with radiation at a rate of 1.5-2 times the left-hand peak) and different annealing characteristics are observed at 70-200°C. These effects are not strongly dependent on the magnitude or sign of the gate voltage during irradiation. These data imply that ionizing radiation creates two different types of interface states as suggested previously [9,22]. The two peaks are separated in surface potential by 90 ±5 mV. The electron capture cross sections associated with these peaks are 5 x 10-16 cm2 (RH peak) and 1.5 x 10^{-14} cm^2 (LH peak) using the Brews analysis [20]. Both values are in the range commonly reported for interface states on n-type silicon [22].

B. Dependence on Dose and Gate Bias

The increase in D_{it} as a function of radiation dose is shown in Fig. 2 for a typical 17.2 nm etchback oxide and a 20.1 nm as-grown oxide for ± 2 MV/cm oxide field applied during irradiation. Straight lines of slope=1 form a good fit to the data at low dose, showing that D_{it} initially increases linearly with dose. At higher doses, D_{it} increases sublinearly with dose.

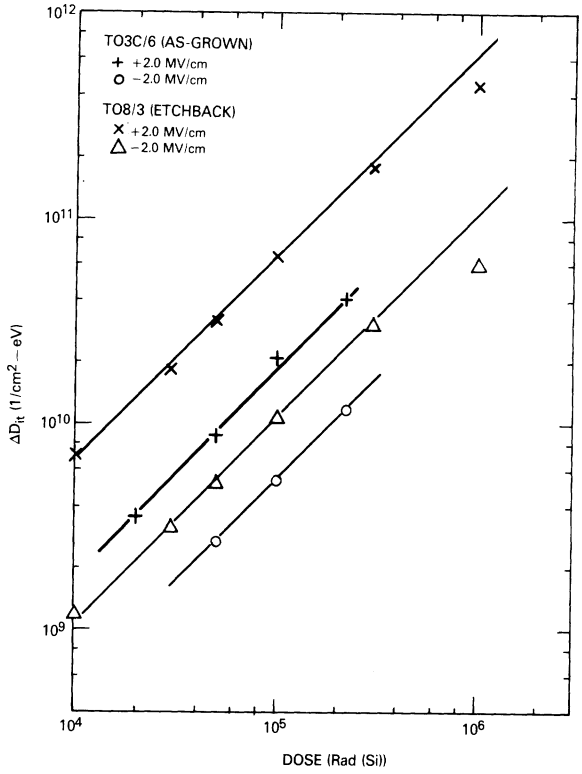

Fig. 2. Dependence of ΔD_{it} on dose for a 20.1 nm as-grown oxide and a 17.2 nm etchback oxide. ΔD_{it} is proportional to dose at low exposures as shown by the straight line fits to the data. The slopes of these lines are used for data points in Figs. 4-5.

The effect of gate bias during irradiation is shown in Fig. 3 for a 17.2 nm etchback oxide at 5 x 10^4 Rad. D_{it} increases with radiation faster at positive bias compared to negative bias. The exact shape (i.e., whether the increases are largest at zero or positive bias) is dependent on oxide thickness and was not investigated in detail. Qualitatively similar results are observed for the as-grown oxides. The oxide field E_{ox} (top axis of Fig. 3) has been calculated taking into account the initial flatband voltage of the sample and the amount of (dose-rate dependent) band-bending in the silicon substate. This band-bending, measured under actual irradiation conditions for each sample with the quasistatic technique [21], is at most about 0.5V, which is a significant correction only for the thinnest oxides. Because of the strong dependence of ΔD_{it} on E_{ox} during irradiation, it is essential to compare ΔD_{it} values for different oxide thickness at the same E_{ox}. In the following data, we have chosen E_{ox} = ±2 MV/cm (values for which ΔD_{it} is relatively insensitive to E_{ox}) to minimize errors.

C. Dependence on Oxide Thickness

The main experimental findings of this paper are

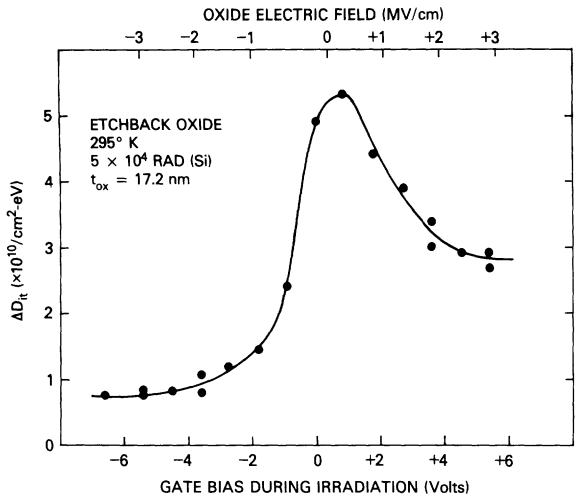

Fig. 3. Dependence of ΔD_{it} on gate bias applied during each irradiation in an etchback oxide. The calculated oxide field is shown at the top of the Figure.

shown in Figures 4 and 5. These Figures show the rates of D_{it} formation per 10^6 rad(Si) dose in the linear regime as a function of oxide thickness for etchback and as-grown oxides. For relatively thick oxides (t_{ox}>12 nm), ΔD_{it}/Mrad may be expressed as t_{ox}^n, where n is a function of oxide type and value of E_{ox}. Experimental values of n have been obtained from a least-squares fit to the data for t_{ox}>12 nm. For the etchback oxides (Fig. 4), n=1.17 ±0.32 at +2 MV/cm and 0.52±0.34 at -2 MV/cm [24]. In the as-grown oxides (Fig. 5), n values are significantly larger at 1.55 and 1.01 at +2 and -2 MV/cm, respectively. In some cases, data from 2-3 samples of the same thickness are shown in Fig. 4 to demonstrate the degree of data reproducibility. Sample-to-sample variations were occasionally larger than known experimental errors, especially at negative E_{ox}. This variation appears to be caused partly by variations across the wafer since data from adjacent capacitors typically showed negligible differences when irradiated under identical conditions.

Ideally, the experimental ΔD_{it}/Mrad rates should be the same for as-grown and etchback oxides at the original growth thickness of the etchback oxide. Unfortunately, in this work the two types of oxides have come from different (although nominally identical) process lots, and we find that ΔD_{it}/Mrad for the etchback oxides to be factors of 2.9 and 2.3 larger at +2 and -2 MV/cm, respectively, compared with the as-grown oxides at 47 nm.

For very thin oxides (t_{ox}<12 nm), the rate of increase in D_{it} is very much smaller than extrapolated from the power law behavior for thicker oxides (Fig. 4,5). For example, in a 6 nm as-grown oxide at +2 MV/cm, the measured ΔD_{it}/Mrad rate is a factor of 16 smaller than predicted by extrapolation of the power law. This thin oxide effect was observed for both oxide types at both ±2 MV/cm oxide fields.

In Fig. 6, flatband voltage shifts ΔV_{fb} obtained from 1 kHz C-V measurements are shown for as-grown oxides versus oxide thickness to show the magnitude of radiation-induced oxide trapped charge Q_{ot} which accompanies D_{it} generation. (Qualitatively similar results were obtained for the etchback oxides.) Especially for very thin oxides, substantial annealing (reduction) of ΔV_{fb} occurred during the time required for the irradiations and measurement, and therefore the measured values in Fig. 6 are somewhat smaller than would have been observed immediately following irradiation. Also,

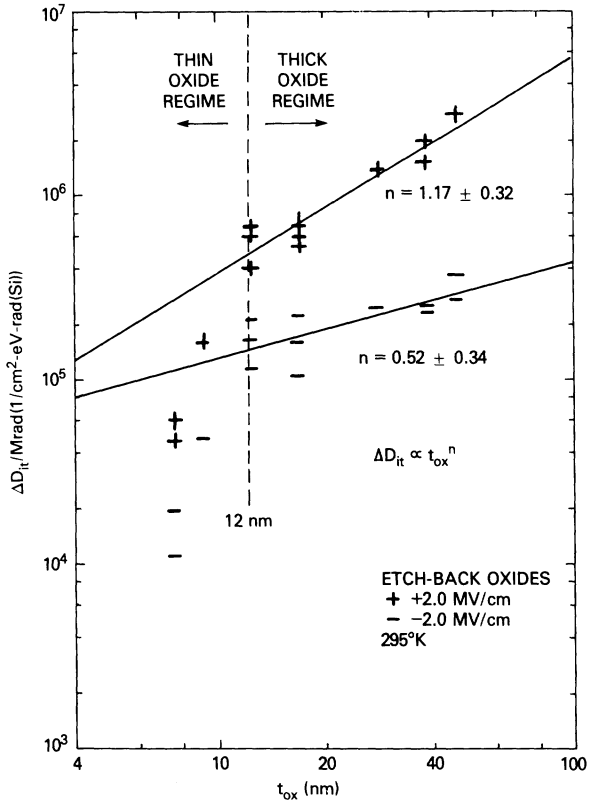

Fig. 4. Dependence of D_{it} creation on oxide thickness for etchback oxides at ±2 MV/cm. Relatively thick oxides show t_{ox}^n power-law dependence. At +2 MV/cm, n≅1 in agreement with several models. The non-zero n value at -2 MV/cm is more difficult to explain (see text).

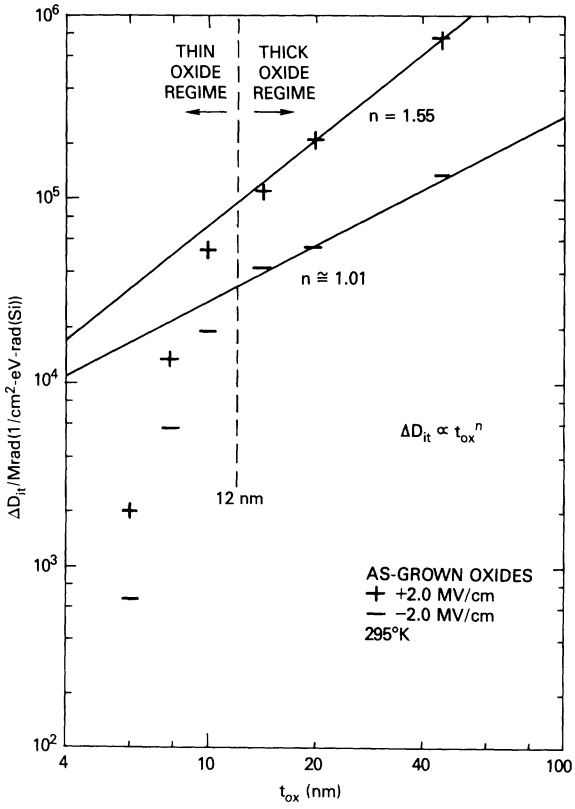

Fig. 5. Dependence of D_{it} creation rate on t_{ox} for as-grown oxides at ±2 MV/cm. Relatively thick oxides have power law t_{ox}^n dependence with larger n values compared to etch-back oxides (see text).

some of the observed flatband shift may arise from charge in interface states rather than fixed oxide charge. A plot of midgap C-V shifts would have been preferable in Fig. 6 to minimize charge contributions from interface states, but this cannot be obtained from 1 KHz data. Despite these errors, radiation-induced Q_{ot} in very thin oxides appears to be anomalously small which parallels the thickness dependence of radiation-induced D_{it}. For relatively thick as-grown oxides, ΔV_{fb} is approximately proportional to t_{ox}^3, in qualitative agreement with previous measurements [3,13].

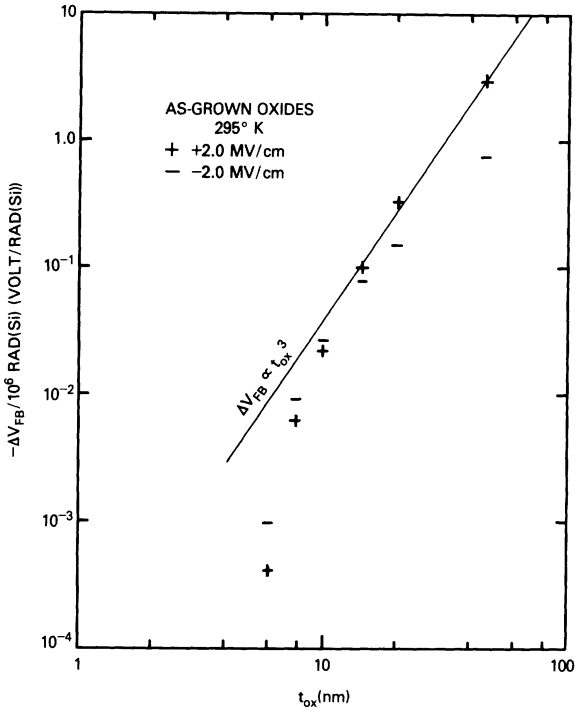

Fig. 6. Radiation-induced flatband shifts in as-grown oxides as a function of oxide thickness at ±2 MV/cm ΔV_{fb} is anomalously small for very thin oxides, similar to the ΔD_{it} data.

DISCUSSION

A. Review of Models for D_{it} Generation

In this section, the important features of several existing models of D_{it} formation by ionizing radiation will be briefly reviewed. Experimental data will then be discussed in light of these models. Detailed reviews of D_{it} generation may be found elsewhere [9,11].

The main effect of ionizing radiation in the gate oxide of MOS devices is creation of electron-hole pairs which results in the accumulation of positive oxide charge Q_{ot} and the formation of fast states D_{it} at the $Si-SiO_2$ interface. Avalanche injection experiments have shown that typical interface state creation rates are relatively low for injected electrons (ΔD_{it}/electron $\cong 10^{-5}$ [25]) but are much higher for injected holes (ΔD_{it}/hole = ≅1 [7]). Since typical D_{it} creation rates are in the range 10^{-3} to 1 per e-h pair (depending strongly on the sample and radiation conditions), holes rather than electrons are believed to be dominant in D_{it} formation. (ΔD_{it}/e-h pair creation rates are on the order of 1-10 % here--see section D).

Recent electron spin resonance data [26] show that one type of interface state is trivalent silicon at the $Si-SiO_2$ interface. This silicon atom is back-bonded to three silicon atoms in the substrate, and the remaining silicon bond is satisfied by a hydrogen-containing specie in the oxide. When the relatively weak hydrogen-silicon bond is broken, a new interface state is formed [9]. However, two main features of this model are still not well understood: First, what is the detailed chemical nature of the interaction leading to bond breakage and D_{it} formation? Second, how do mobile holes created in the oxide bulk induce D_{it} formation at the $Si-SiO_2$ interface?

Some physical models which have been developed to address the second question are: (1) The "two-stage" hole model, in which holes created by radiation in the oxide bulk drift (for positive gate bias) to and are trapped at the $Si-SiO_2$ interface. In the second stage, some trapped holes are converted via a relatively slow process to D_{it} [27], and others remain as Q_{ot}. (2) The positive ion model, proposed to explain some of the details of the dependence of D_{it} formation on oxide field, in which holes are trapped in the oxide bulk, in turn releasing a positive ion (probably H+) for transport to the interface [14]. (3) The radiolytic hydrogen model due to Griscom [28], in which neutral hydrogen is released by hole trapping in the oxide bulk and diffuses to the $Si-SiO_2$ interface. The hydrogen combines with an interface state precursor and an electron from the substrate to form an interface state. A dependence on oxide field enters this model because of the need to pull an electron from the substrate to complete the D_{it} reaction, not because of drift through the oxide of a positively-charged species as in the previous two models.

B. Dependence on Etch-back Oxide Thickness (t_{ox}>12 nm)

The number of holes created in an oxide by ionizing radiation is proportional to its thickness t_{ox}. Therefore, the hole transport model predicts D_{it} formation proportional to t_{ox} for positive E_{ox}. This agrees with experimental results for etchback oxides at +2 MV/cm (Fig. 4), where ΔD_{it} increases as t_{ox}^n, with n=1.17±0.32. For the positive ion and neutral hydrogen models, the production of D_{it} will depend on other oxide properties in addition to t_{ox}, such as hole trap or hydrogen distribution in the oxide; however, assuming uniform distributions, then these other models also predict D_{it} formation proportional to t_{ox}.

For the etchback oxide in Fig. 4, we find that ΔD_{it}/Mrad is much smaller at -2 MV/cm compared to +2 MV/cm, and increases relatively weakly as t_{ox}^n, n=0.52 ± 0.34. Despite scatter in the data, the n=0 hypothesis can be rejected at the 99% confidence level. How is this negative bias result to be explained? The hole transport and positive ion models in their simplest forms do not appear suitable since positively charged species should not drift to the interface under negative bias. Close to the $Si-SiO_2$ interface, radiation-induced holes or ions could interact with defects to produce D_{it} even at negative E_{ox}. A rough estimate of the effective thickness of this layer can be obtained from the ratio of the magnitudes of D_{it} increase at +2 and -2 MV/cm, which is about 5 for the 17 nm oxide in Fig. 4. This suggests that the effective interaction distance is about 3.5 nm, which does not seem physically unreasonable. However, this mechanism still would not produce ΔD_{it}/rad which increases with t_{ox}, since the interaction distance would not depend on oxide thickness.

The negative field data appears to be in better agreement with the radiolytic hydrogen model [28]. In this model, since the hydrogen diffuses in its neutral state, presumably the same amount of hydrogen reaches the interface independent of the oxide field direction. Under negative bias, interface state formation cannot proceed as under positive bias when electrons from the

substrate combine with the interfacial hydrogen to produce D_{it}. However, for long irradiations (as used here), radiation-induced electrons from the oxide bulk continuously pass through the $Si-SiO_2$ interface during irradiation. Since the supply of both electrons and radiolytic hydrogen increases with increasing t_{ox}, this will lead to increasing D_{it} formation as a function of t_{ox} at negative E_{ox}. Clearly further work on the field and time dependence of D_{it} formation should be undertaken.

The negative field effect could be caused by the additional processing that etchback samples undergo after the oxide etch. For example, the amount of hydrogen that diffuses into the oxide during the final post-metalization anneal could depend on the oxide thickness, which could affect its radiation sensitivity. However, the fact that the n value at positive bias for the etchback samples is nearly equal to 1.0 suggests that this effect is not large, since the response of a non-uniform oxide would be affected at positive as well as negative oxide fields. It is also possible that D_{it} formation at negative bias is caused simply by a different mechanism than which dominates at positive bias. For example, recent evidence that there are "prompt" and "slow" mechanisms of D_{it} formation [29], support the idea that two independent mechanisms may exist.

C. Comparison of As-grown and Etchback Oxides

Comparing results from Figures 4 and 5, ΔD_{it}/Mrad depends more strongly on oxide thickness in as-grown oxides than in etchback oxides. The experimental power law exponents n are 1.55 and 1.01 for the as-grown oxides at +2 and -2 MV/cm, respectively, compared to n=1.17 and 0.52 for the etchback oxides. Similarly, larger n values were obtained for as-grown compared to etchback oxides (n=3.0 versus 2.0, respectively) in measurements of radiation-induced flatband and threshold voltage shifts [13]. This difference was interpreted as being due to an increase in the density of interfacial defects/trapping sites with increasing oxide thickness [13]. This correlation may in turn be explained by relief of interfacial stress creating additional interfacial traps [30,31]. The data here appears in agreement with this model, although the actual difference in slope factor found here between etchback and as-grown oxides is 0.4-0.5 as opposed to a value of 1.0 in ref [13]. The is most likely due to the lower oxide growth temperature of 900°C compared to 1000°C in ref. [13].

D. Dependence on Applied Field

As shown in Fig. 3, ΔD_{it} is largest when E_{ox} applied during irradiation is nearly zero. This dependence on E_{ox} is similar to that reported previously for a 47 nm pyrogenic oxide [4]. In general, this behavior is different from that reported in thicker oxides, where ΔD_{it} is typically much larger at large positive E_{ox} and increases with increasing E_{ox} up to about 4 MV/cm [ref. 6, Fig. 4]. It is somewhat surprising that ΔD_{it} peaks at low field values because geminate recombination of electron-hole pairs created in the oxide might be expected to reduce the effective hole creation rate (and thus the rate of D_{it} formation) for E_{ox} less than 10^6 V/cm [32]. Geminate recombination occurs when the oxide field is too weak to separate mutually attractive electron-hole pairs.

One explanation for the large D_{it} creation rate near $Vg \cong 0$ V is that geminate recombination is suppressed in very thin oxides [19]. For example, at 80°K the ratio of the effective number of holes trapped in the oxide for $Vg \cong 0$ V compared to E_{ox}=+2 MV/cm is about 0.1 for a 91 nm oxide but is 0.9 for a 10 nm oxide [19]. Assuming that the 80°K data is applicable at 295°K, this ratio is about 0.4 for a 17 nm oxide in Fig. 3. Other possible explanations for the anomalous field dependence lie in the field dependence of other processes involved in D_{it} formation. For example, the probability of hole trapping has been shown to decrease with oxide field approximately as $E_{ox}^{-1/2}$ [33]. Finally, we remark that radiation-induced trapped positive charge ΔQ_{ot}, measured here by flatband voltage shifts, was also generally larger near zero than it was at large positive E_{ox}.

In the three models of D_{it} formation discussed above, the process begins with radiation-induced hole generation. There are a number of competing processes, and not all holes result in D_{it} formation. Holes may cause trapped oxide charge, or they may escape the oxide completely (see Section E below). An approximate value for the number of interface states generated during irradiation per hole created in the oxide ("D_{it} yield") is obtained from the measured D_{it} (assumed constant across the bandgap) with the assumption that only one interface state is created per hole [7]. The number of e-h pairs created by the radiation can be calculated from ref [32] (assuming no geminate recombination--see above.) For the data in Fig. 3, the calculated D_{it} yield is 8% at the maximum, falling to about 1% at -2 MV/cm. Since many previous measurements of D_{it} show that D_{it} increases near the band edges, the assumption of an energy-independent D_{it} may somewhat underestimate the D_{it} yield. Nevertheless, this approximate calculation shows that only a minority of the radiation-induced holes in these thin oxides ultimately result in D_{it} formation. By comparison, ΔV_{fb} for the 17 nm oxide is about 0.1 V/Mrad(Si) (Fig. 6), so only about 1% of the total holes created by radiation in this oxide remain as trapped oxide charge. Consequently, it appears that for this 17 nm oxide sample, at least 90% of the holes are not involved in either of the major radiation damage effects.

E. Thin Oxide Results (t_{ox}<12 nm)

For very thin oxides (t_{ox}<12 nm), the rate of increase in D_{it} with radiation is substantially smaller than would be extrapolated from the power law behavior of the thicker oxides (Figs. 4-5). This same effect is observed for both as-grown and etchback oxides, at both ±2 MV/cm oxide fields, and the deviation from power law dependence occurs at about the same oxide thickness (12 nm). A similar result has been reported previously for very thin tunnel oxides, where no increase in D_{it} was observed (within experimental error) following radiation to 8 Mrad for a 5 nm oxide [18]. The experimental sensitivity in that work was about 2×10^{10} states/cm^2-eV, for a ΔD_{it}/Mrad rate of 2.5×10^3 states/cm^2-eV-Rad, a value which is not in disagreement with data here (see Fig. 5). Similarly, significantly reduced hole trapping has been observed in flatband and threshold shift data in very thin oxides here (Fig. 6) and previously at 295°K [4,15-18] and at 80°K [19].

There may be several causes of reduced D_{it} formation and hole trapping in very thin oxides. First, as proposed by Ma and Barker[18], trapped holes may tunnel out of the thin oxide before D_{it} formation can take place. Studies of reduced flatband shifts in thin oxides at 295°K [15-18, 34] and at 80°K [19], and calculations of tunneling discharge [34], strongly support this tunneling concept. Since the thin oxide regime occurs for t_{ox}<12 nm in Figs. 4-5, the effective hole tunneling distance must be at most 6 nm. This is in reasonable agreement with previous results of 4 nm at 80°K [19] and up to 6 nm at 300°K [34]. Secondly, the oxide's properties may be substantially different in thin oxides because the interfacial regions make up a large fraction of the toal oxide volume. For example,

hole trap/defect [13] and hydrogen concentrations [35] are believed to be higher in the interfacial regions; thus one might expect increased radiation sensitivity in thin oxides. This is of course contrary to experimental results given here.

SUMMARY

The rate of increase in interface state formation caused by ionizing radiation has been studied as a function of oxide thickness in etchback and as-grown oxides. Several experimental steps have been taken--namely the use of etchback oxides, as low a radiation dose as possible, and the same oxide field during irradiation for different oxide thicknesses--to provide improved data for testing model predictions. Ac conductance measurements in thin (t_{ox}<30 nm) oxides suggest the occurrence of two distinct types of interface states after irradiation. At +2 MV/cm, ΔD_{it}/rad increases as $t_{ox}^{1.17}$ in etchback oxides, which within experimental error is in reasonable agreement with the models ($t_{ox}^{1.0}$ predicted) assuming that hole creation is the important rate-limiting step. At -2 MV/cm, ΔD_{it}/rad increases as $t_{ox}^{0.52}$ which cannot be easily explained by either the hole or positive ion transport models, but which is at least qualitatively explained by Griscom's radiolytic hydrogen model [28]. Several similarities have been observed between D_{it} generation and generation of radiation-induced fixed positive charge, suggesting that both effects arise from the same fundamental mechanism, hole generation in the oxide.

For as-grown oxides, interface state formation also obeys a power-law t_{ox}^{n} dependence, where the value of n is 0.4-0.5 larger than for the etchback oxides at ± 2 MV/cm. For the +2 MV/cm data, this result is in agreement with the interfacial stress model which proposes that the interfacial defect/trap density increases with oxide thickness and oxidation time.

For very thin (t_{ox}<12 nm) etchback and as-grown oxides at both +2 and -2 MV/cm, the rate of D_{it} formaion is very much smaller than extrapolated from power-law behavior of the thicker oxides. This effect appears to be caused by tunneling of radiation-induced holes out of the oxide before conversion of the holes to interface states (by whatever process) can occur.

ACKNOWLEDGEMENTS

We would like to thank the staff of the NRL Microelectronics Processing Facility for sample fabrication; Dr. Akos Revesz for discussions concerning hydrogen in oxides; Mr. Doug Bentz for collecting much of the data; and the Defense Nuclear Agency for its partial support of this work.

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