Heavy-Ion-Induced Breakdown in Ultra-Thin Gate Oxides and High-k Dielectrics

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***Abstract*—We present experimental results on single-event-induced breakdown in sub-5-nm plasma-enhanced SiO_2, nitrided SiO_2, Al_2O_3, HfO_2, and $Zr_{0.4}Si_{1.6}O_4$ dielectrics typical of current and future-generation commercial gate oxides. These advanced oxides are found to be quite resistant to ion-induced breakdown. Radiation-induced soft breakdown was observed in some films with 342 MeV Au (LET $=$ 80 MeV/mg/cm^2) but not 340 MeV I (LET $=$ 60 MeV/mg/cm^2). The critical voltage to hard breakdown was found to scale with the square root of the physical oxide thickness, not with the energy stored on the gate capacitance. Alternative dielectrics with equivalent oxide thickness substantially below their physical thickness were found to exhibit significantly higher voltage to hard breakdown than SiO_2 counterparts. All of the samples reached ion-induced hard breakdown at applied voltages well above typical operating power-supply voltages; these findings bode well for the use of advanced commercial integrated circuits in space systems.**

***Index Terms*—Dielectric breakdown, dielectric reliability, scaling, single-event radiation effects.**

I. Introduction

SINGLE-EVENT-INDUCED dielectric breakdown is an insulating failure in a gate dielectric due to exposure to heavy ions [1]. The conditions for such failures are acute in power MOSFET devices where large device capacitances and high voltages can contribute sufficient energy to destroy a gate insulator given the trigger of a single-event-induced conduction path across the dielectric [2]. Gate rupture failures have been observed in ground-based experiments and are suspect in space-based operation [3].

Concern that similar catastrophic failures would be seen in low-power integrated circuits operating in the harsh environment of space has been growing over the past few years. There are several developments fueling this concern. In 1994, Swift *et al.* observed anomalous stuck bits in 4-Mbit dynamic random-access memories (DRAMs) exposed to low-fluence heavy-ion irradiation [4]; this group speculated that the effect could be due to gate rupture, which until that time had been observed only in high-power devices. As it was not known how this effect might scale with technology, the use of advanced technologies in space missions was at issue. Concurrently, dielectric breakdown was observed in submicrometer digital technologies when exposed to electrical stressing (hot-electron or hot-hole injection) experiments [5]. Thus, commercial reliability concerns developed. Scaling trends to oxides under 5 nm, the acceptance of gate dielectric fields above 5 MV/cm, and the use of alternative dielectrics with unknown breakdown properties have all exacerbated concerns related to oxide degradation and premature failure under stressed conditions.

It has been shown that electrically induced and radiation-induced stressing of ultrathin oxides are very similar in many respects. Since advanced commercial (nonradiation-hardened) technologies are finding increased use in space systems, concern exists over the potential for catastrophic gate insulator failures at normal operating voltages when parts are exposed to the harsh, heavy-ion environment of space [6].

In 1997, Sexton *et al.* performed a study of heavy-ion-induced gate rupture in SiO_2 films of thicknesses of 18, 12, and 6.5 nm [7]. These oxides exhibited an increase in critical field to rupture with decreasing oxide thickness, leaving intriguing questions about the future relationship between dielectric scaling and radiation-induced oxide breakdown as commercial technologies advance and new dielectric materials are introduced. Followup work in 1998 by Sexton *et al.* [8] and Johnston *et al.* [9] shed considerable light on breakdown mechanisms in gate dielectrics, particularly soft breakdown versus gate rupture. However, there is still controversy within the community with respect to the potential for gate breakdown failures in space and the impact of technology scaling on the prospects for next-generation technologies in space applications.

In this paper, we investigate heavy-ion radiation-induced soft breakdown (RSB) and hard breakdown [(RHB)—also called single-event gate rupture (SEGR)] in sub-5-nm gate insulators, including plasma-enhanced oxides, nitrided oxides, and three high-k dielectrics of interest in deep submicrometer commercial technologies: Al_2O_3, $Zr_{0.4}Si_{1.6}O_4$, and HfO_2. These oxides are representative of current and future-generation commercial gate dielectrics that could find use in space systems. We

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report the similarities (and, more importantly, the differences) of electrical-stressing reliability to dielectric breakdown under heavy-ion radiation, the suitability of ultrathin and advanced, high-k dielectrics for space applications, and the relationship of radiation-induced dielectric breakdown trends to commercial scaling trends predicted by the SIA National Technology Roadmap for future generation technologies.

II. Phenomenological View of Gate Dielectric Breakdown

Stress-induced breakdown of thin oxides is a topic of considerable import and study within the semiconductor reliability community [10]–[13]. While the mechanisms leading to stress-related oxide damage and the physics of the resultant current conduction across damaged oxides are subjects of debate among reliability groups, there are phenomenological aspects of the process that are fairly well accepted.

Electrical-stress-induced breakdown in very thin oxides has been attributed to a multistage degradation process. During high-field stressing, defects are created in the oxide. Sufficient defects can lead to the appearance of one or more low-resistance paths across the insulator. A "percolation path" of defects is a widely accepted breakdown structure, although the microscopic structure and conduction mechanism are still of considerable debate. Current through these conduction paths can enhance the damage and lead to the onset of more severe breakdown mechanisms—soft (SBD) or hard (HBD) breakdown. The distinction between soft and hard breakdown is often attributed to a stable conduction path (soft) versus a catastrophically expanding path (hard) [12].

In terms of observable electrical device response, soft breakdown is most often associated with an anomalous increase in gate leakage current [above the expected stress-induced leakage current level], while hard breakdown is associated with insulating failure and ohmic conduction across the dielectric [10]. Stress-related soft breakdown is dominant in very thin oxides and low-power devices. Stress-related hard breakdown dominates dielectric failures in thicker oxides and power devices. Fig. 1 (after [14]) shows a generally accepted view of the phenomenological current–voltage attributes of soft versus hard breakdown in thin oxides.

Our study focuses on the hard breakdown phenomenon under heavy-ion exposure, which was clearly observed in our test dielectrics. We also observed soft breakdown due to both heavy-ion and electrical stressing in some, but not all, of the oxides tested.

III. Test Structures and Experimental Techniques

SiO_2, Al_2O_3, HfO_2, and $Zr_{0.4}Si_{1.6}O_4$ capacitor structures fabricated at North Carolina State University [15] were used in this single-event breakdown study. Planar MOS capacitors of two sizes ($50 \times 50\ \mu m$ and $100 \times 100\ \mu m$) were fabricated using remote plasma-enhanced chemical vapor deposition (RPECVD) of a base oxide followed by N_2/He plasma nitridation. Base oxidation plus four N_2 carrier gas concentrations (5%, 10%, 15%, 20%) was used to establish nitrided oxides on $\langle 100 \rangle$ p-type silicon (forming a common cathode plate) with thicknesses of 3.3 and 2.2 nm. Al_2O_3, $Zr_{0.4}Si_{1.6}O_4$, and HfO_2 dielectrics were RPECVD deposited on HF-last $\langle 100 \rangle$ p-type silicon over a thin SiO_2 layer (0.6-nm interfacial SiO_2) to form a dielectric stack. The physical thickness of the Al_2O_3 was 5.4 nm (4.8-nm Al_2O_3 + 0.6-nm interfacial SiO_2) with an equivalent oxide thickness (EOT) of 2.6 nm (verified by CV and nuclear reaction profiling). Similarly, the $Zr_{0.4}Si_{1.6}O_4$ had a physical thickness of 4.5 nm with an EOT of 2.3 nm, and the HfO_2 had a physical thickness of 70 nm and an EOT of 9 nm. In the nitrided oxide case, the anode plate was formed by n+ polysilicon with aluminum as the contact. In the other cases, the anode was aluminum.

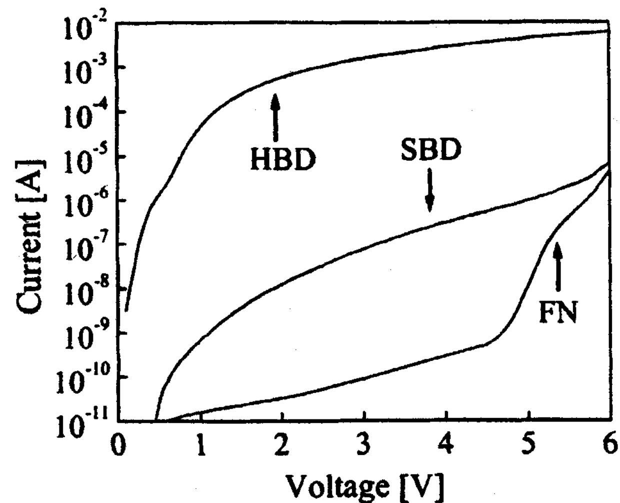

Fig. 1. Qualitative view of electrical-stress-induced SBD versus HBD. Also shown is a typical Fowler–Nordheim tunneling current curve. After [14].

Preirradiation electrical testing of the capacitors included capacitance–voltage measurements, charge to breakdown (Q_{BD}) measurements using the linear voltage stressing technique [16], voltage to breakdown using the fast voltage sweep method of [17], and capacitance-based EOT extraction.

Single-event testing was performed at the Brookhaven National Laboratory Tandem Van de Graaff facility using 342-MeV gold, 340-MeV iodine, and 285-MeV bromine ions at normal incidence. The total fluence per shot was typically 10^6 ions/cm^2, so that each capacitor under test would receive less than 100 ions per exposure—low enough to ensure minimal precursor damage but high enough to ensure heavy ion strikes to the capacitor. Breakdown measurements were performed using the method described by Sexton *et al.* [7]: irradiate under a constant dc applied bias, perform a postirradiation current–voltage sweep, increment dc bias, repeat. To isolate single-event-induced breakdown from electrical stress related breakdown, all voltage sweep limits were chosen to limit preirradiation Fowler–Nordheim (FN) tunneling well below the measured limit for electrical breakdown.

IV. Results

A. Electrical Characterization

Extensive electrical characterization of the capacitors, including voltage to breakdown (V_{BD}) and charge to breakdown (Q_{BD}) tests, were performed prior to heavy-ion irradiation

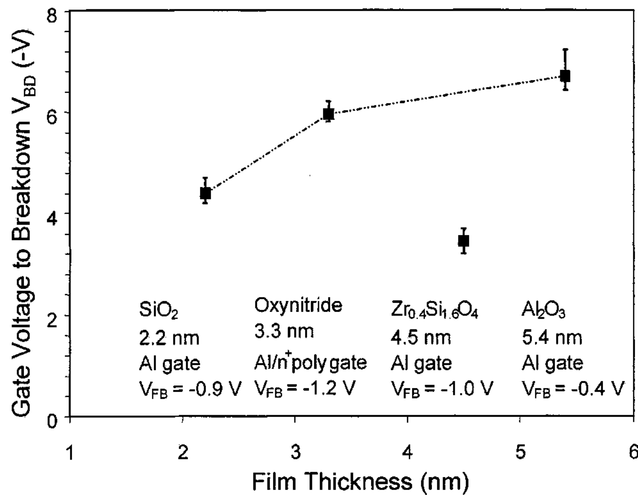

Fig. 2. Extracted voltage to breakdown under the step-stress electrical stressing conditions described in the text.

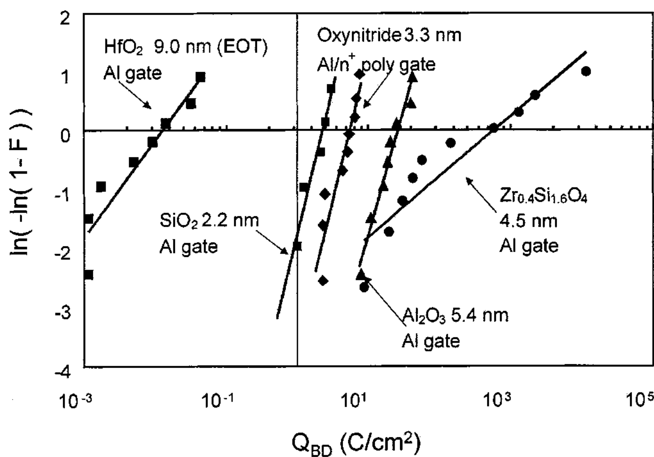

Fig. 3. Cumulative Weibull distribution of charge to breakdown under electrical stress condition as in Fig. 2. The size of capacitors is $50 \times 50\ \mu m^2$.

testing. V_{BD} measurements used the same voltage ramp stressing sequence as that of the heavy-ion experiments. The method to determine breakdown was consecutive comparisons of average measured current during a low voltage sweep. This method of extracting V_{BD} produced values that were within a standard deviation of those measured using the common 1-MV/cm/s linear voltage ramping method. Results of these preirradiation breakdown measurements are shown in Fig. 2.

To explore the electric field to breakdown, flat band voltages of each film were calculated via high-frequency capacitance data. In all cases except ZrSiO (discussed later), the equivalent (to SiO_2) critical electric field was over 10 MV/cm.

Q_{BD} measurements were performed by numerical integration of measured current during voltage stresses up to abrupt current increase. Fig. 3 shows the cumulative Weibull distribution of Q_{BD} for the films used in this experiment. The large value in the ZrSiO case was due to a high level of leakage current at intermediate gate voltages.

Note that the ZrSiO film showed high leakage current and a low voltage to breakdown, indicating a less than device-quality starting film; subsequent results reflect the lower intrinsic film

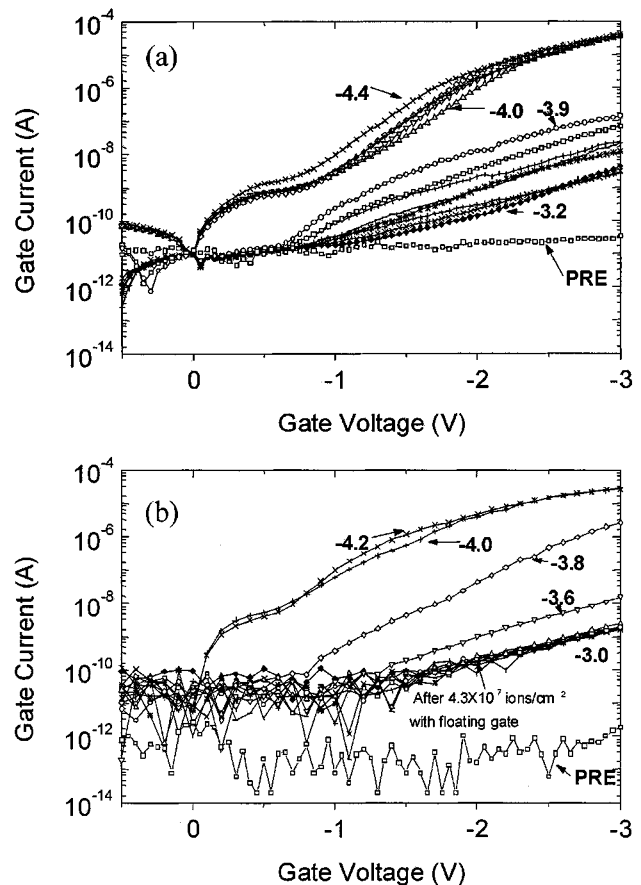

Fig. 4. Oxide current versus applied voltage following biased irradiation for 3.3-nm SiO_2 (a) $100 \times 100\ \mu m$ and (b) $50 \times 50\ \mu m$ capacitors showing RSB (below 4.0 V bias) and RHB (at 4.0 V bias). Labeled values are irradiation bias in volts. The irradiation ion was 342-MeV Au.

quality of the ZrSiO material available in this study. The HfO_2 Q_{BD} levels are lower than those observed for SiO_2, but this is mitigated by its high dielectric constant, reducing the physical electrical field required to achieve equivalent operation to SiO_2. The value of Q_{BD} for SiO_2 is quite reasonable for research oxides.

B. Single-Event Test Results

1) 3.3-nm SiO_2 Capacitors: Fig. 4 shows typical single event-induced breakdown results (typical of nine data sets for each capacitor size) for the 3.3-nm SiO_2 oxide capacitors. Each curve represents an I–V sweep following biased exposure to 342-MeV Au ions (LET $= 82$ MeV/mg/cm^2), with increasing dc bias applied during the irradiation for each curve. The fluence per irradiation step was 10^6 ions/cm^2.

The curves of Fig. 4 show the two-step breakdown dependence on bias voltage during irradiation, as shown qualitatively in Fig. 1: stage 1 at irradiation voltages between -3.2 and -3.9 V, stage 2 at the irradiation voltage of -4.0 V. This observation was consistent across all of our 342-MeV Au data for these 3.3-nm SiO_2 capacitors and is quite similar to radiation results observed by Sexton *et al.* [7] for thicker SiO_2 dielectrics. Sexton *et al.* attributed the characteristic two-stage I–V response to soft breakdown before single-event gate rupture (hard breakdown). Similar observations have been made in the reliability

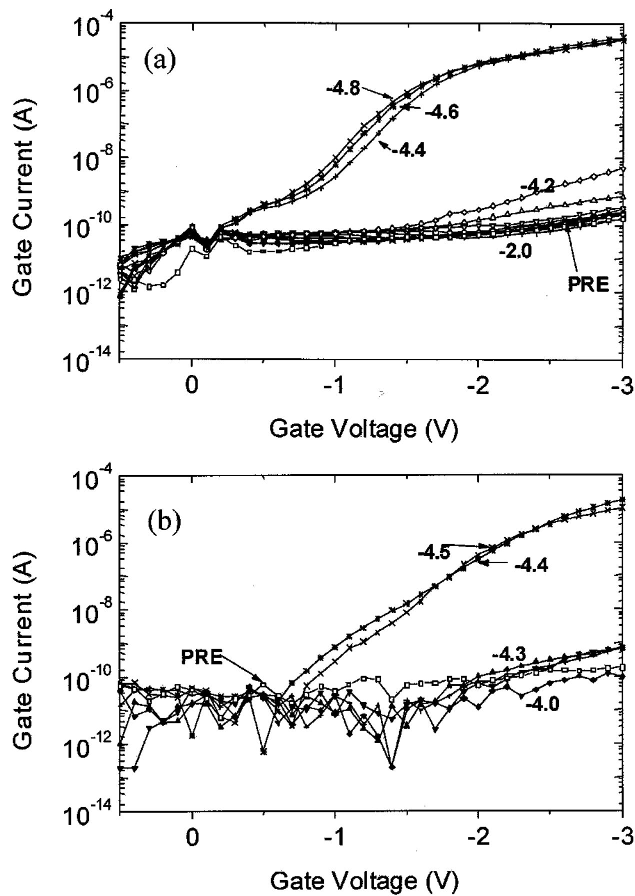

Fig. 5. Oxide current versus applied voltage for 3.3-nm SiO_2 (a) 100 × 100 μm and (b) 50 × 50 μm irradiated capacitors. Labeled values are irradiation bias. The irradiation ion was 340-MeV iodine. Note that significant RSB is not observed.

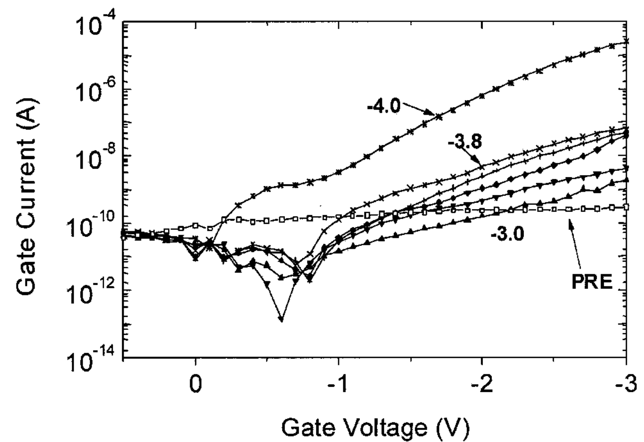

Fig. 6. Oxide current versus applied voltage for 3.3-nm 15% N SiO_2 100 × 100 μm capacitors. Labeled values are irradiation bias. The irradiation ion was 342-MeV Au.

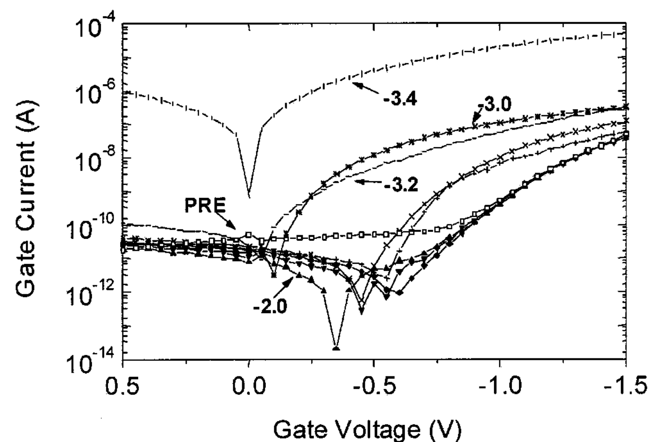

Fig. 7. Oxide current versus applied voltage for 2.2-nm SiO_2 100 × 100 μm capacitors. Labeled values are irradiation bias. The irradiation ion was 342-MeV Au.

community for thin oxides under electrical stressing measurements; these have also been attributed to soft (or quasi) breakdown versus hard (or catastrophic) breakdown [10], [11]. The distinction is important, since the possible failure thresholds implicated are quite different; hard failures are often predicted to be rare in oxides thinner than 5 nm, whereas soft breakdown has been cited as a potential reliability concern in space systems [18].

Across our data, we observed no discernible difference in the hard breakdown voltage during heavy-ion exposure between the small and large capacitor structures. This observation has important implications when interpreting the failure mechanism, as discussed in Section V.

Data collected on these capacitor structures when exposed to 340-MeV iodine ions (LET= 60 MeV/mg/cm^2) are shown in Fig. 5. These capacitors showed similar hard breakdown characteristics to the capacitors exposed to Au, with onset of breakdown at slightly higher irradiation bias levels. While the purpose of this work was to study scaling trends and not the dependence of breakdown on LET, the LET dependence in our data is consistent with that reported by other groups [7], [8], [19]. For this study, note particularly the lack of soft breakdown with these lighter ions.

2) 3.3-nm 15% N SiO_2 Capacitors: Breakdown data under exposure to 342-MeV Au ions for the 3.3-nm oxides deposited using a 15% N_2 source gas were collected on nine capacitor structures. Representative results are shown in Fig. 6. Again, a two-step distribution of I–V curves was seen. We saw no statistically significant difference in the threshold voltage to hard breakdown characteristics for the nitrided oxides compared to the pure oxide.

3) 2.2-nm SiO_2 Capacitors: Representative data collected on six 100 × 100 μm 2.2-nm SiO_2 capacitors exposed to 342-MeV Au ions are shown in Fig. 7. These curves continue to exhibit a two-stage breakdown (soft, then hard) for the larger capacitors and a one-stage hard breakdown for the smaller capacitors. Although the threshold voltages to breakdown were lower, the 2.2-nm capacitors behaved qualitatively like the thicker 3.3-nm oxide structures.

4) 2.6-nm (EOT) Al_2O_3 Capacitors: Fig. 8 shows representative data from five 2.6-nm (EOT) Al_2O_3 alternative–dielectric capacitors (5.4-nm physical stack thickness) exposed to 342-MeV Au ions. This distinctive pattern of minimal leakage, no soft breakdown, and catastrophic failure was consistent across all of our test samples in this group.

5) 9.0-nm (EOT) HfO_2 Capacitors: Thicker alternative dielectric hafnium oxide structures were irradiated with 342-MeV

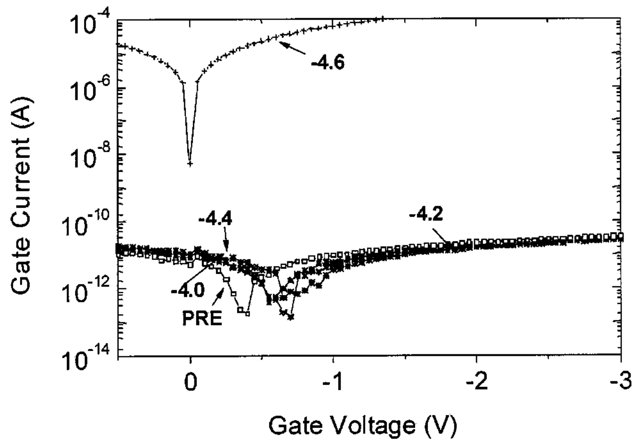

Fig. 8. Oxide current versus applied voltage for 2.6-nm (EOT) Al_2O_3 100 × 100 μm capacitors. Labeled values are irradiation bias. The irradiation ion was 342-MeV Au.

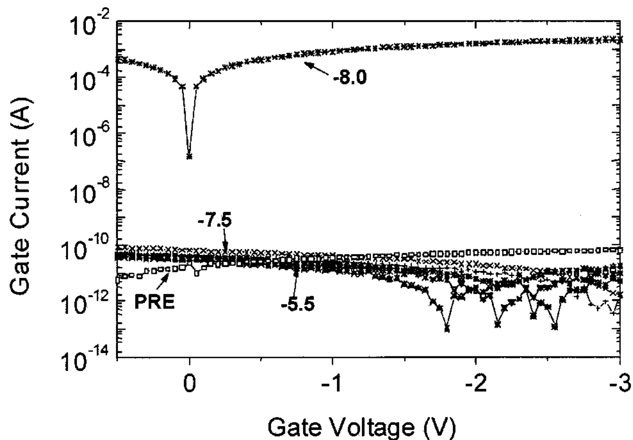

Fig. 9. Oxide current versus applied voltage for 9.0-nm (EOT) HfO_2 50 × 50 μm capacitors. Labeled values are irradiation bias. The irradiation ion was 342-MeV Au.

Au ions. Representative results of three 50 × 50 μm 9.0-nm EOT capacitors are shown in Fig. 9. Like the Al_2O_3 films, the hafnium oxides exhibited no soft breakdown before the onset of hard failure.

6) 2.3-nm (EOT) $Zr_{0.4}Si_{1.6}O_4$ Capacitors: Fig. 10 shows data for 2.3-nm (EOT) $Zr_{0.4}Si_{1.6}O_4$ 100 × 100 μm capacitor structures (4.5-nm physical thickness) irradiated with 342-MeV Au ions. Two capacitors were tested and both exhibited the same unusual two-step hard breakdown, as can be seen in the figure. This unique behavior may be related to the intrinsic preirradiation leakage observed in these oxides. As discussed in Section IV-A, the ZrSiO dielectrics exhibited substantial intrinsic oxide damage, preirradiation leakage, and a low intrinsic electrical breakdown voltage. These dielectrics were laboratory samples and not yet of production quality. Even so, the voltage to radiation hard breakdown was still above the intrinsic electrical breakdown voltage level and would be well above the requirements for VLSI applications.

It has been postulated [9] that precursor damage (due to irradiation or electrical stressing) can influence the onset of radiation-induced hard breakdown. Since the ZrSiO insulators exhibited a wide $Q_{\rm BD}$ Weibull distribution prior to irradiation testing

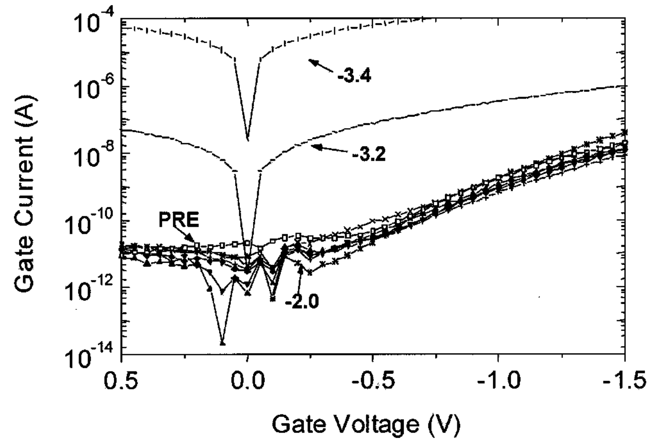

Fig. 10. Oxide current versus applied voltage for 2.3-nm (EOT) $Zr_{0.4}Si_{1.6}O_4$ 100 × 100 μm capacitors. Labeled values are irradiation bias. The irradiation ion was 342-MeV Au.

(Fig. 3), it is not surprising that both the intrinsic electrical and extrinsic radiation breakdown of this insulator are degraded by the extreme variability in prestress oxide quality. However, note that soft breakdown was not observed, even in this research-quality dielectric. In the case where prestress damage is so severe as to affect the intrinsic electrical breakdown of a dielectric, radiation-induced breakdown would be of minimal practical concern.

V. Analysis

A. Oxide Breakdown Due to Electrical Stressing

Hard breakdown is prominent in thick oxides under high fields (as would be seen in power semiconductor devices), with onset often described by the energy dissipated within the conducting conduit: 1/2 CV^2. Stress-related hard breakdown is rarely seen in sub-5-nm oxides [12], [13]; on the other hand, soft breakdown is often observed and is considered the dominant stress-related breakdown mode in emerging oxides. Soft breakdown exhibits a power-law I–V relationship and has been attributed to a conducting pipe that is stable, but does not generate sufficient thermal energy to expand. Alam *et al.* [20] have explained soft breakdown as a conduction path across the dielectric, which dissipates power ($V^2/R_{\rm path}$) below the threshold for irreversible thermal damage, with a crossover to hard failure given by a specific power (not energy) level. As we show later in this section, we see a similar power-related threshold for single-ion-induced hard breakdown in our tests.

We induced soft breakdown in the SiO_2 oxides of our test via both electrical stressing and heavy-ion exposure. The I–V signatures were analogous in both cases. We did not observe soft breakdown in any of the alternative dielectrics tested under heavy-ion exposure, but did induce soft breakdown with electrical stressing.

It should be noted that the question of whether electrically induced soft breakdown constitutes a "failure" is hotly debated within the reliability community. Clearly, enhanced oxide leakage associated with soft breakdown is of concern for emerging technologies. However, modern circuits based on scaled devices are designed to tolerate gate leakage: sub-5-nm

oxides exhibit considerable intrinsic tunneling currents [21]. Thus, the full implications of stress-induced soft breakdown have yet to be established. On the other hand, there is little dispute that hard breakdown constitutes a catastrophic failure mechanism.

B. Soft Versus Hard Breakdown Under Heavy-Ion Exposure

The I–V signatures of breakdown from electrical and radiation stress are similar and have analogous naming conventions. Adopting the terminology of others [7], [9], [22], we use RSB for "radiation-induced soft breakdown," the cumulative increase in leakage current shown in Fig. 1. We use RHB for "radiation-induced hard breakdown" (also called SEGR) to denote the catastrophic breakdown signature.

Ceschia *et al.* have suggested that RSB arises from conductive paths created by damage along each ion track and distributed across the device in rough similarity to the ion fluence [19]. This group also observed no threshold oxide field for the onset of enhanced radiation-induced leakage current or RSB. Our data are consistent with those observations. Referring to Fig. 4, the increase in leakage current for each subsequent ion shot and at each irradiation voltage step clearly indicates a cumulative damage effect. This increase in current cannot be explained by cumulative conductive tracks alone (there is an 8$\times$ increase in fluence between the 3.2-V curve and the 3.9-V curve; the current increases by approximately 50$\times$). Clearly, irradiation bias contributes to RSB. This is further supported by the data of Fig. 11. This figure shows the same oxides exposed to 342-MeV Au ions under a 0-V irradiation bias. The oxide leakage currents observed are a factor of 1.5 lower than those observed in Fig. 4 under irradiation bias for the same fluence.

Note from Fig. 5 that iodine (LET $=$ 60 MeV/mg/cm^2) exposure did not cause RSB—a consistent observation across all of our measurements. However, zero biased parts exposed to a significant 342-MeV Au fluence prior to breakdown tests exhibited enhanced preirradiation leakage. Enhanced leakage or RSB was often observed at first bias. Fig. 11 shows 3.3-nm SiO_2 capacitors exposed to 342-MeV Au and 185-MeV Br ions with a 0-V bias applied during irradiation. Clearly, the Au ions damage the oxide and contribute to RSB with no bias applied. Bromine, however, exhibited no effect on SBD.

Our data support a synergistic effect of conditions for RSB: conduction tracks created by ions of high LET (LET $=$ 60 MeV/mg/cm^2 or higher in our tests) and current flow due to an applied irradiation bias leading to localized damage regions. This observation is consistent with the work of Ceschia *et al.* [19] and Sexton *et al.* [7]. The key to these observations is that RSB is clearly a cumulative effect tightly coupled to test fluence and bias and is only observed for the most energetic ions. This is important in our later discussions of failure modes.

Hard breakdown, on the other hand, does not appear closely coupled to fluence. Sexton *et al.* suggested a lack of influence of precursor damage to the onset of SEGR in SiO_2 oxides [8], and our data on thinner oxides support that conclusion. Fig. 12 shows I–V curves for 3.3-nm SiO_2 capacitors that were exposed (unbiased) to 4.4 $\times$ 10^7 ions/cm^2 fluence prior to breakdown testing and exhibit a HBD of $-$3.6 V to $-$3.8 V. Upon comparison with Fig. 4, there is no strong correlation of hard breakdown to preexposure to ion fluence. Also, as can be seen in Fig. 4, RHB is not a cumulative effect, as is RSB. In all cases, at the onset of RHB, we observed a distinctive step in oxide current and the signature HBD I–V curve shown in Fig. 1 (in particular, oxide conduction at nearly zero applied bias), with little further degradation for continued ion exposure or increased oxide bias (voltage steps $-$4.1 V through $-$4.4 V in Fig. 4). We observed

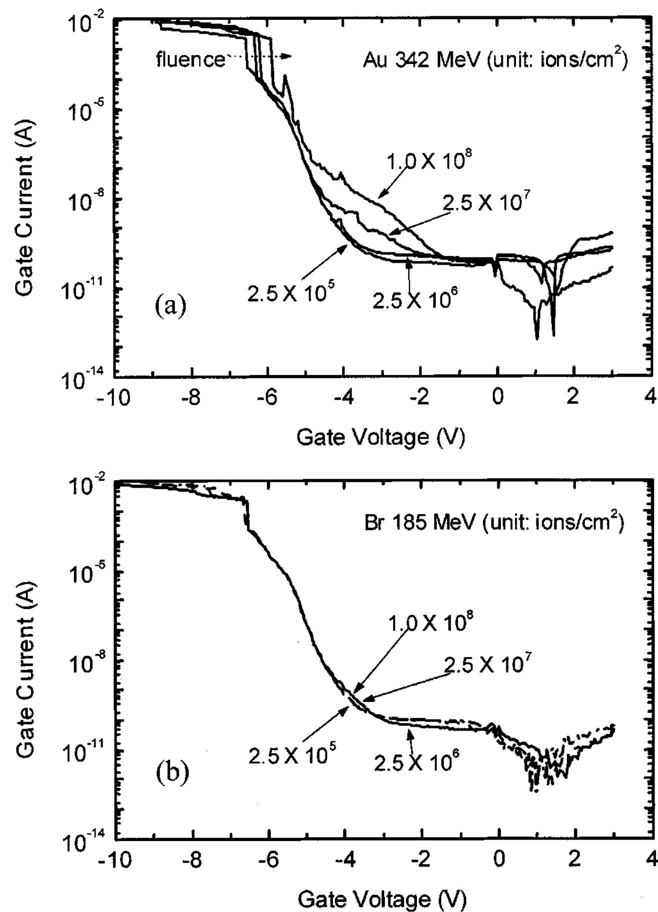

Fig. 11. Damage effects due to unbiased heavy-ion exposure. In (a), 342-MeV Au ions (LET $=$ 80 MeV/mg/cm^2) at the fluence levels shown contribute to enhanced leakage and a reduced intrinsic electrical breakdown. In (b), 185-MeV Br ions (LET $=$ 40 MeV/mg/cm^2) do not.

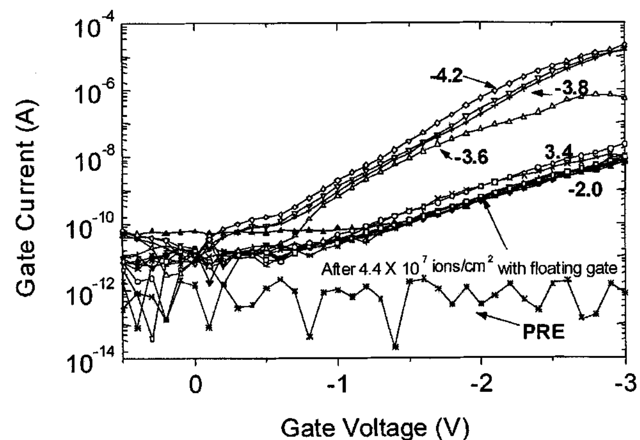

Fig. 12. 3.3-nm SiO_2 oxide exposed to 4.4 $\times$ 10^7 ions/cm^2 fluence prior to radiation testing. Note HBD at 3.8 V, similar to the virgin oxides of Fig. 4.

RHB at fluence levels as low as approximately 25 strikes per capacitor, supporting the conclusion that RHB is essentially a single-ion phenomenon.

C. Soft Breakdown Due to Single-Event Radiation Stressing—Is It a Practical Concern?

Electrical stress and single-event soft breakdown mechanisms are very similar, with the single-event ion track replacing high-field tunneling in the creation of oxide damage and subsequent trap-assisted conducting paths. In either case, the ultimate effect is enhanced leakage influenced by stress level (either electrical charge injection or radiation fluence). A secondary damage effect, demonstrated by Weir *et al.* [11], is an increase in $1/f$ noise. Because electrical soft breakdown is considered a significant reliability issue for commercial parts, it has been suggested that radiation soft breakdown is also a possible failure mode of concern for space systems. Based on our data, we conclude that RSB is *not* an enhanced failure mode of significance for digital VLSI using advanced oxides and alternative dielectrics.

It has been suggested that even a single ion-induced RSB damage region could affect circuit reliability in space [18]. Our data are not consistent with that assertion, at least for digital VLSI operation. Consider Fig. 4. At the irradiation bias of -3.2 V, this part received a fluence of 1.1×10^6 ions/cm^2. The leakage current at -3 V on the I–V sweep is 4.2×10^{-9} A. This corresponds to approximately 40 pA of leakage per ion-damaged conduction conduit. At an irradiation bias of -3.9 V, the leakage current at a test bias of -3 V corresponds to approximately 175 pA per ion track. It is difficult to envision a circuit application where such current levels (due to a single ion) would promulgate a digital circuit failure.

Also, recall that we observed RSB only for Au ions (LET $= 80$ MeV/mg/cm^2) and not I ions (LET $= 60$ MeV/mv/cm^2). This is consistent with work by Ceschia *et al.* [23], who observed RSB only with very high LET particles. The flux of ions at or above an LET of 60 MeV/mg/cm^2 in a quiet (long-term average) geosynchronous space environment is approximately 0.0023 ions/cm^2/y [24]. Submicrometer gate dimensions associated with the oxide thicknesses of study here would be 0.18 μm or less. A typical gate region of 0.18 μm $\times$ 0.36 μm would thus expect to see strikes of ions capable of producing damage associated with RSB once every 6.7×10^{11} y. Clearly, the prospects of multiple such hits to a single gate (sufficient to produce the cumulative RSB damage observed in our beam experiments) are negligible.

D. Single-Event-Induced Hard Breakdown—Critical Applied Voltages

While the cumulative effects of damage associated with RSB are extremely unlikely in a space environment, the possibility of a single-ion hit capable of inducing SEGR is quite likely, assuming that suitable electric field conditions exist. Using the typical values of device sizes and the quiet space environment given in the previous section, the frequency of strike by a particle of LET higher than 40 MeV/mg/cm^2 (demonstrated to cause RHB and equivalent to 290-MeV Br) to a next-generation 4-Gbit DRAM would be approximately every four years. Since

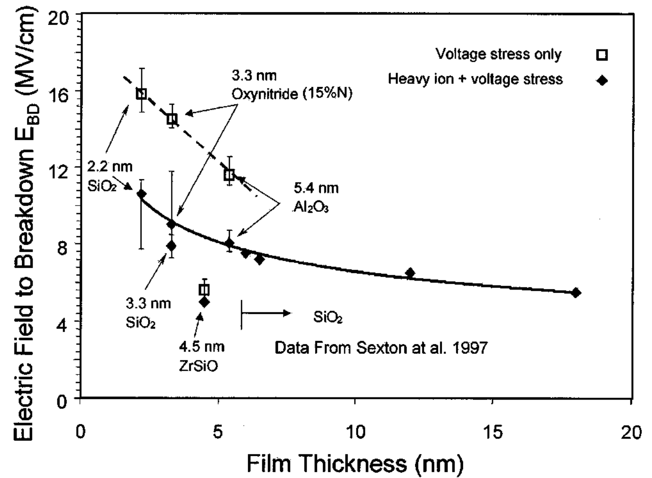

Fig. 13. Critical electric field to breakdown under voltage stress and exposure to 342-MeV Au ions for the capacitor samples tested. HfO_2 does not appear on this scale.

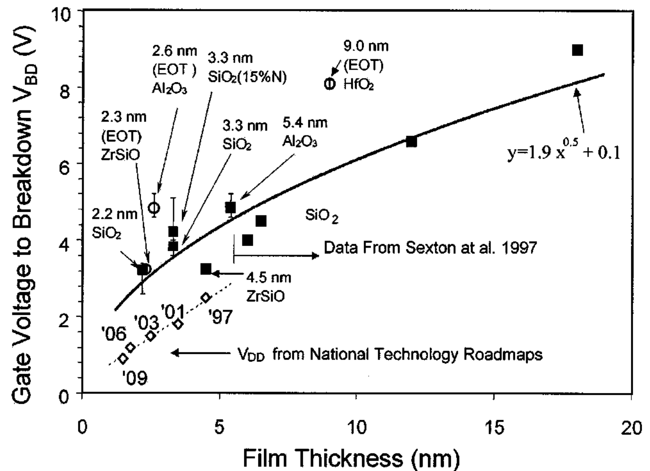

Fig. 14. Trends for V_{RHB}, the voltage to radiation-induced hard breakdown, with physical dielectric film thickness for exposure to 342-MeV Au ions. Also shown are data from [7] for comparison. The solid curve represents an empirical model based on a constant oxide power dissipation to breakdown, as described in the text.

RHB is a single-ion failure mode, this creates the potential for a reliability concern over the life of a space mission (we later show that typical operating voltages alleviate this concern).

Fig. 13 shows the electric field that led to hard breakdown under exposure to 342-MeV Au ions for our samples. Note the increasing E_{RBD} trend with scaling to thinner dielectrics. Also shown in the figure are intrinsic, prestress oxide breakdown fields (E_{BD}). Note the considerable differences in slope. Clearly, E_{RBD} does not scale with the same basis set as intrinsic breakdown, as has been observed by Titus *et al.*in power MOSFETs [25].

Radiation-induced hard breakdown critical voltages V_{RHB} were extracted from our data as the lowest irradiation bias causing the characteristic HBD signature I–V curve (e.g., -4.0 V in Fig. 4). Fig. 14 summarizes our measurements of V_{RHB} for 342-MeV Au exposure as a function of film thickness for the dielectrics of this work. The error bars in the figure represent variations across our sample set, and the data points represent the mean value. For comparison, data from [7] are also plotted.

There has been speculation that RHB is linked to an energy dissipation model (1/2 CV^2), as often applied to gate rupture in thick-oxide high-voltage devices. Since our data show insignificant differences between V_{RHB} in the large and small capacitor structures, a simple energy storage failure mode (proportional to capacitance) is unlikely. Sune *et al.* [26] have suggested that electrical HBD and SBD have the same origin (localized damage regions), with the difference due to the size of the post-damage conduit. In the heavy-ion case, this damage spot size would be related to the ion LET and the localized power dissipated via the conduit current. A power threshold model, such as that of Alam *et al.* [20], when applied to the radiation-induced breakdown case, fits our V_{RHB} data quite well. If a threshold power dissipation ($P = V^2/R_{\mathrm{path}}$) controls the transition from RSB to RHB, then V_{RHB} should scale with $R_{\mathrm{path}}^{1/2}$. For a fixed ion LET, we would expect the equivalent conduction resistance along the path to scale with path length through the oxide. Thus, V_{RHB} would also scale with $t^{1/2}$, where t is the physical oxide thickness. The solid curve in Fig. 14 represents the equation

$$V_{\mathrm{RBD}} = K\sqrt{t_{\mathrm{physical}}} + \phi$$

where t is the physical oxide thickness in nm, K is a calibration parameter most probably related to the heavy ion LET ($K = 1.9$ in this case), and ϕ (0.1 V in this case) is 1/2 of our irradiation voltage step size (to account for the intrinsic quantization error of our measurement ramp). It appears that our $t^{1/2}$ model adequately describes the relationship between physical oxide thickness and the voltage threshold for RHB.

E. Breakdown Properties of Alternative Dielectrics

The breakdown voltage properties of the three alternative dielectrics we studied are also shown in Fig. 14. Note that the breakdown voltage follows the $t^{1/2}$ model applied to physical dielectric thickness. However, since high-k dielectrics exhibit an equivalent oxide thickness thinner than their physical thickness (due to increased capacitance), the practical voltage to breakdown is actually considerably better than equivalent SiO_2 counterparts. Note in Fig. 14 the V_{RBD} values for $ZrSiO_2$, Al_2O_3, and HfO_2 EOTs. In particular, a comparison of the 2.2-nm SiO_2 with the 2.6-nm EOT Al_2O_3 data shows a considerable improvement in the voltage to hard breakdown.

Fig. 14 also shows a tight correlation of V_{RHB} with the physical oxide thickness, not the equivalent thickness, of the alternative dielectrics as predicted by the V^2/R power dissipation model of Section V-D. The oxide capacitance, and thus the energy stored, are not good predictors of hard breakdown, as would be expected from the (1/2)CV^2 breakdown model often applied to power devices.

The ZrSiO dielectric did not show the substantial increase in V_{RBD} above the physical thickness trend line, as seen with the Al_2O_3 and HfO_2. We attribute this to the significant intrinsic leakage exhibited with these capacitor structures—the preirradiation quality of these oxides was not of the same order as the SiO_2 and Al_2O_3 oxides tested.

In addition to desirable V_{RHB} values, these high-k dielectrics exhibited no radiation-induced soft breakdown. These results bode very well for the use of advanced dielectrics in commercial parts destined for space missions.

F. Scaling Trends

In addition to our voltage breakdown data, Fig. 14 also shows V_{DD} values as a function of equivalent oxide thickness for future IC generations as suggested by the SIA National Technology Roadmap [27]. Note that in all cases, our data are significantly above the power-supply voltages that would be seen in commercial technologies fabricated with these gate dielectrics. Because of the disparity between our measured breakdown voltages and expected voltages under normal circuit operation for these ultrathin dielectrics, we do not expect RHB to be a significant problem for space systems employing next-generation commercial integrated circuits operating at standard power-supply voltages.

VI. Summary and Conclusions

We have studied heavy-ion-induced soft and hard breakdown in sub-5-nm oxides and advanced dielectrics (SiO_2, $SiNO_2$, Al_2O_3, $Zr_{0.4}Si_{1.6}O_4$, HfO_2). Our data support a synergistic set of conditions leading to the localized damage conduits of radiation soft breakdown—applied irradiation bias and high-fluence high-LET ion exposure. However, we found the current levels associated with individual RSB conduits to be below a level that constitutes circuit failure. RSB was not observed under exposure to 340-MeV Iodine ions or in any of our alternative dielectrics. We do not believe RSB is a failure mode of significant concern for space deployment of emerging digital VLSI technologies.

RHB was observed in all of our samples when exposed to 342-MeV Au and 340-MeV Iodine ions; however, the critical field to breakdown was found to increase significantly with scaling for these films. The voltage threshold to breakdown (V_{RBD}) was not strongly influenced by pretest fluence or by capacitor size. RHB appears to be related to a power dissipation model for the ion damage track, and V_{RBD} was shown to track with the square root of the dielectric physical (not equivalent) thickness. Our Al_2O_3 and HfO_2 alternative dielectrics, with equivalent oxide thickness below the physical film thickness, exhibited enhanced resistance to breakdown relative to comparable SiO_2 films.

All of the films tested exhibited breakdown voltages well above the operating voltages predicted by the SIA National Technology Roadmap, even under exposure to 342-MeV Au ions. Our results bode very well for the use of advanced commercial circuits employing ultrathin and alternative dielectrics in space applications.

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