Effects of Ion Atomic Number on Single-Event Gate Rupture (SEGR) Susceptibility of Power MOSFETs

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35-WORD ABSTRACT
The relative importance of heavy-ion interaction with the oxide, charge ionized in the epilayer, and charge ionized in the drain substrate, on the bias for SEGR failure is experimentally investigated.

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I. INTRODUCTION

Single-event gate rupture (SEGR) remains a key failure mode in vertical power MOSFETs flown in space-based missions. These devices are vulnerable to this failure mode when biased in the off state. Fig. 1 shows an illustration of a typical n-type VDMOS. The lightly-doped epitaxial layer can range from around 10 μm to 120 μm thick for devices with 100 V to 1000 V breakdown ratings. It is this thickness combined with the light doping that permits the formation of a large depletion region needed to hold off such high drain voltages, preventing high fields from developing in the silicon or gate oxide. Beneath this epilayer region is the highly doped drain substrate which lowers the drain contact resistance, helps to remove heat, and mechanically strengthens the die. Due to this high substrate doping concentration, the drain voltage is transferred with minimal loss from the drain contact to the base of the epilayer.

As first suggested by Fisher [1], the mechanisms of SEGR involve both the heavy-ion interaction with the gate oxide and the charge ionization in the epitaxial layer of the device. The passage of the ion through the gate oxide temporarily reduces the electric field required for dielectric breakdown; the ionized charge within the epilayer collapses the depletion region, allowing a greater portion of the high off-state drain voltage to fall across the gate oxide. More recently, it has been suggested that the charge ionized within the highly-doped drain substrate region also contributes to the maximum transient electric field across the oxide [2]. The following work seeks to enhance our understanding of the importance of these mechanisms relative to one another, as well as the importance of the ion atomic number versus ion linear energy transfer (LET).

The relative contributions of the different mechanisms to SEGR in a vertical power MOSFET are experimentally assessed through careful selection of monoenergetic ion beams based upon their average LET within the device epilayer. In this way, the threshold drain-source voltage (Vds) at which SEGR occurs can be compared for ions of differing atomic numbers (Z) that ionize the same average total charge within the epilayer. In addition, two ion beams are chosen such that the ion with lower atomic number ionizes on average slightly more charge throughout the epilayer and a substantial portion of the substrate than does the ion with higher atomic number. Conclusions are drawn from analysis of the ion beam species and energy deposition profiles as a function of the threshold Vds determined for the given ion beam, and from expected behavior based upon the Titus-Wheatley formula [3], which is validated for the power MOSFET used in this work.

II. EXPERIMENTAL METHODS

A radiation-hardened 200 V n-type vertical power MOSFET (VDMOS) was used for these experiments. Samples came from two wafers having the same lot date code. Heavy-ion test data were taken at the Texas A&M University Cyclotron Facility (TAMU). For each sample, the gate-source bias was held at -10 V to assure that SEGR would occur during exposure to lighter, lower-LET ions. At this bias, effects of multiple proximal ion impacts are reduced [4, 5], making the data easier to interpret. Vds was incremented in 5-volt steps; at each step, the sample was irradiated until either the sample failed or a fluence of $3x10^5$ ions/cm^2 was reached. A post-irradiation gate stress test was then performed to reveal any latent damage to the gate oxide. Failure was defined by the gate leakage current exceeding the 100 nA vendor specification for Igss.

The ion LET versus penetration depth in silicon is plotted in Fig. 2 for the six monoenergetic ion beams selected for this study. The ion species and energies were chosen to yield two pairs of beams having similar incident LETs and total charge ionization within the sample epilayer, and one pair in which the lower-Z ion yielded a higher LET throughout the epilayer and the initial portion of the highly-doped drain substrate. Table I provides the surface-incident LET, LET at the oxide, mean LET in the epilayer region, and total charge ionized within the epilayer, as calculated with the OMERE, v. 3.4.5.0, Equivalent LET software module based on SRIM 2006 [6, 7].

III. RESULTS

The threshold Vds for SEGR was determined for six different monoenergetic heavy-ion beams. For four of these beams, the ions and energies were chosen to yield pairs that would on average ionize the same total charge of either 7.9 pC or 15.5 pC within the sensitive epilayer of the samples. In addition, one heavy-ion beam in each pairing has minimal penetration into the substrate, whereas the other beam has significant penetration into the substrate. In this way, the effect of ion LET within the epilayer was dampened to reveal any ion species or substrate effects on SEGR susceptibility. In this abstract, we describe only the results from the first pair, showing plots of results of both pairs.

The first pairing consisted of irradiations by either 422 MeV Cu (Z = 29) or 1089 MeV Kr (Z = 36). Three or four samples, respectively, were irradiated at a fixed -10 Vgs, with the threshold Vds for SEGR found by incrementing Vds by 5V per beam run. Due to the small sample size and the interval nature of the data from the experiments in this study, all data were analyzed as follows: We assume that for each ion species and energy, the SEGR failure Vds interval for the device tested has a normal distribution from part-to-part variability. The method of maximum likelihood was then employed to identify the mean (μ) and standard deviation (σ) best fitting the experimental data. To further account for the limited data set and hence the unknown extent of part-to-part variability, we use the standard deviation at the boundary of the 95% confidence level (CL) instead of this best fit value, using the Chi-square value for 2 degrees of freedom (μ and σ).

Fig. 3 plots these means for the Cu and Kr data, with error bars indicating one standard deviation from the mean at the boundary of the 95% CL. As can be seen for the data taken at -10 Vgs, despite both ions on average ionizing equal amounts of charge within the epilayer, SEGR occurs at a lower Vds under irradiation with the heavier Kr ion. The difference in the mean Vds for SEGR is significant at the 95% CL. As shown in Fig. 3, we further characterized the effect of Cu versus Kr ions by irradiating two additional samples with 422 MeV Cu, holding Vds at 130 V (a value within the failure range for Kr), and incrementing Vgs by -1 to -2 volts. SEGR occurred in both samples between -16 Vgs and -17 Vgs or -18 Vgs. These data further support this apparent ion species effect, although the contribution of charge ionized within the highly-doped substrate cannot be ruled out at this point.

We tested a second pairing of ions (discussed in the full paper, but shown in Fig. 4). The data show a difference between the two ion species but this shift in the mean is not significant at the 95% CL.

Lastly, we compare the bias necessary for SEGR under irradiation with 1405 MeV Ag versus 2950 MeV Xe. Irradiations were performed at -10 Vgs bias on 3 samples per beam condition following the same procedures as before. Despite the Ag ions having a higher average LET throughout the epilayer and into a substantial portion of the drain substrate region (see Fig. 2), a higher applied Vds was necessary for SEGR to occur at -10 Vgs with Ag as compared with the heavier species, Xe (Fig. 5). This difference in failure threshold is significant at the 95% CL. This difference was further substantiated by irradiating 2 additional samples with 1405 MeV Ag at a drain bias of 50 Vds, near the mean of the threshold for SEGR from Xe. Both samples experienced SEGR at -14 Vgs, having last survived at either -12 V or -13 V.

To better understand these data, we also validated the Titus-Wheatley formula [3], $V_{gs}crit = (10^7)(t_{ox})/(1+Z/44)$, finding the critical Vgs for SEGR with Vds fixed at 0 V (Fig. 6). (Discussed in the paper, including fitting methods used; in the formula, t_{ox} is the oxide thickness in cm, Z is the ion atomic number.)

IV. DISCUSSION

Past studies have suggested that the ion atomic number may play a role in SEGR susceptibility, beyond simply the ion LET or total charge ionization [3, 8]. To our knowledge, this study is the first to control for the charge ionization in the silicon epilayer in order to examine the impact on SEGR of different ion species. Our results suggest that ion atomic number cannot be neglected when considering SEGR risk avoidance on orbit.

The results presented in Figs. 3-5 have large error bars that represent the 95% worst-case upper bound on the standard deviation for the distribution of failures. The small sample size, Vds interval, part-to-part variability, and the Poisson nature of the failure rate all contribute to this uncertainty in the best-fit standard deviation. Of these factors, the small sample size is likely the largest contributor, such that the significance of the results in this study would likely increase with more data. The impact of the other factors was lessened by a Vds increment of only 2.5% of the rated BVdss, a single lot-date-code for the samples, and a high fluence at each beam run.

As shown in Fig. 4, the higher mean threshold Vds for SEGR for 740 MeV Ag versus 1618 MeV Xe was not significant at the 95% CL. In contrast, the 2950 MeV Xe irradiations resulted in SEGR at a significantly lower Vds than did irradiations with lighter 1405 MeV Ag ions, despite the Ag ions depositing more energy in both the epilayer and the initial 70 μm of highly-doped substrate (Figs. 2, 5). This result suggests that the lack of significance at the 95% CL between 740 MeV Ag and 1618 MeV Xe may be due to the small sample size and the Vds interval size; alternatively, the effect of the ion species on the oxide may lessen as the average LET in the epilayer increases. Additional studies are needed to determine whether or when the energy deposition in the silicon dominates the species effects on the oxide or the importance of ion track structure within the epilayer.

We note that the variability in the Vds for SEGR was largest for the lightest ion tested. This variability may be due to a decreasing cross-section for SEGR as ions become lighter and/or deposit less energy. In addition, the 422 MeV Cu ions were obtained using a 2.8 mil Al degrader resulting in greater energy straggling. In the paper, we discuss and quantify these potential factors.

Charge ionized within the highly-doped drain substrate did not have as much of an effect as the charge in the epilayer or the ion atomic number on the SEGR failure threshold bias. In the case where Ag ionized more charge in both the epilayer and the first 70 μm of the substrate than Xe, the heavier Xe ions ruptured the gate oxide at a lower drain-source bias. Only charge in the initial few μm of the heavily-doped substrate would be expected to contribute to the transient electric field due to the deformation of the epilayer/substrate interface drift field into the first few μm of the substrate at the location of the ion track due to the large concentration of charge ionized; however, in the majority of the substrate there is only a minimal electric field such that charge would be collected primarily by slower diffusion processes. Additionally, this charge would undergo comparatively higher recombination upon initial ionization. The important ion beam characteristics for inducing SEGR therefore are the total energy it can deposit in the epilayer including the epi/substrate interface region, and the ion atomic number.

Finally, we examine the additional Vgs bias required to reduce the threshold Vds of the lighter ion to the Vds threshold found for the heavier ion. In Fig. 3, a 6-V to 7-V increase in Vgs magnitude was required for Cu ions to induce SEGR at the 130 Vds failure threshold determined for Kr. In Fig. 5, a 3-V to 4-V increase in Vgs magnitude was required for Ag ions to induce SEGR at the 50 Vds threshold for Xe. From Fig. 6, we determine that at 0 Vds, the difference in Vgs magnitude for SEGR with Cu versus Kr is 4.6 V, and with Ag versus Xe, 3 V. This difference will be analyzed in the full paper in the context of the oxide response to the ion strike as well as ion track structure effects in the epilayer.

The work presented has SEGR hardness assurance implications which are also addressed in the paper.

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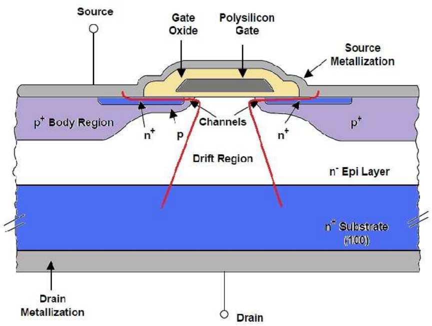

Figure 1. Illustration of a n-type VDMOS.

Table I. Ion Beam Properties for the 200V nVDMOS.

Ion	Energy	Incident LET	LET at Oxide	Mean LET in Epi	Total Charge Ionized in Epi
Z	*MeV*	*MeV·cm²/mg*	*MeV·cm²/mg*	*MeV·cm²/mg*	*pC*
29	422	25.9	26.7	29.3	7.9
36	1089	27.7	28.1	29.3	7.9
47	740	53.8	55.5	57.8	15.5
54	1618	54.6	55.4	57.8	15.5
47	1405	42.7	43.4	45.4	12.2
54	2950	41.5	41.8	42.8	11.5

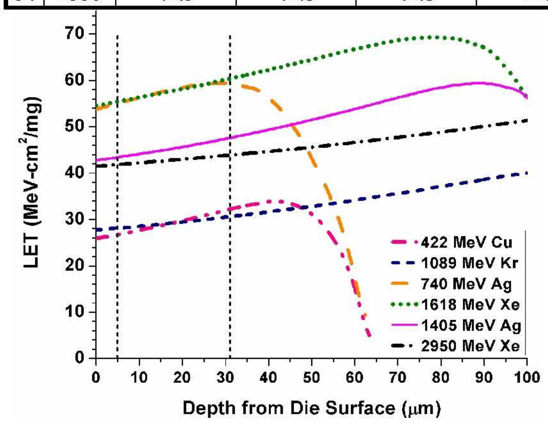

Figure 2. Ion LET as a function of penetration depth. Vertical dashed lines demarcate the epilayer region.

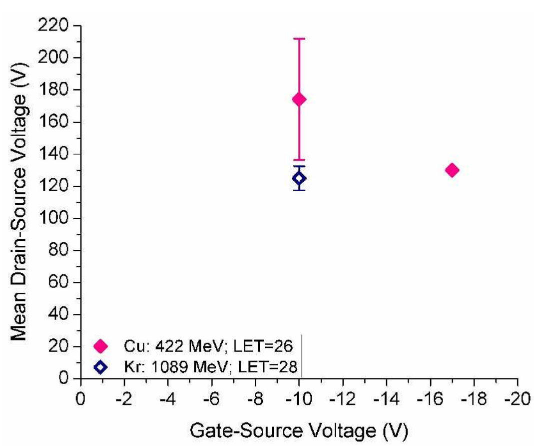

Figure 3. SEGR response curve for Cu versus Kr irradiation.

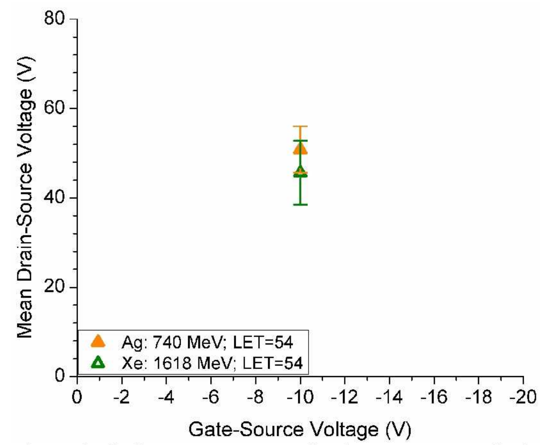

Figure 4. SEGR response curve for Ag versus Xe, at incident LETs of 54 MeV·cm2/mg.

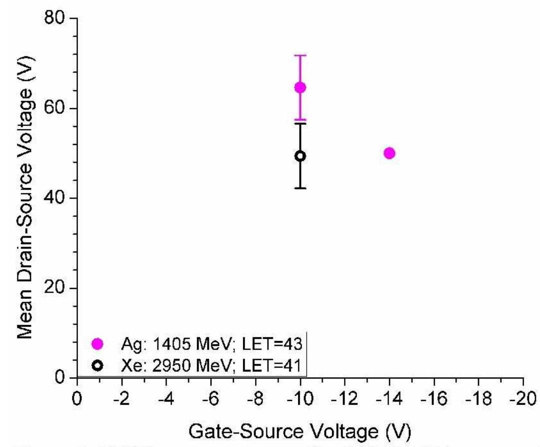

Figure 5. SEGR response curves for 1405 MeV Ag versus 2950 MeV Xe ions.

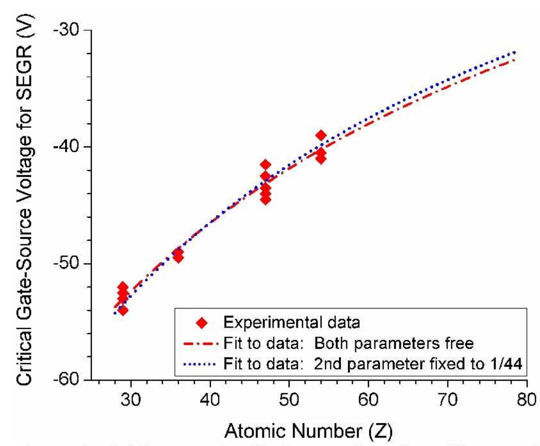

Figure 6. Critical Vgs for SEGR as a function of ion species. Data are fitted to the two-parameter reciprocal function y=A/(1+Bx), with either both parameters free, or with B fixed to that of the Titus-Wheatley formula.