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

Jean-Marie Lauenstein, *Member, IEEE*, Neil Goldsman, Sandra Liu, *Member, IEEE*, Jeffrey L. Titus, *Senior Member, IEEE*, Raymond L. Ladbury, *Member, IEEE*, Hak S. Kim, Anthony M. Phan, Kenneth A. LaBel, *Member, IEEE*, Max Zafrani, and Phillip Sherman, *Member, IEEE*

***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 in vertical power MOSFETs is experimentally investigated. The results indicate that both the charge ionized in the epilayer and the ion atomic number are important parameters of SEGR failure. Implications on SEGR hardness assurance are discussed.**

***Index Terms*—heavy ion, power MOSFET, single-event gate rupture (SEGR)**

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 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 ion passage 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. This transient increase of the oxide electric field is thought to result from charge separation due to the vertical drift field in the epilayer, where for an n-type VDMOS the electrons are transported from the oxide/silicon interface toward the drain contact faster than the holes can be transported laterally to the body region [2]. 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 [3]. 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).

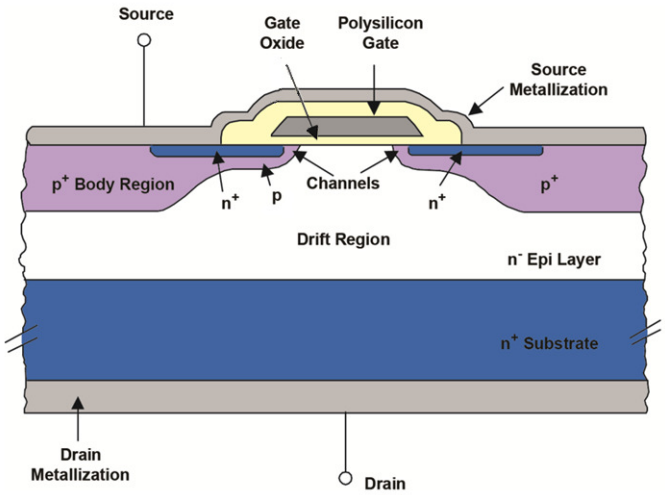

Fig. 1. Illustration of n-type VDMOS cross-section.

The relative contributions of the different mechanisms to SEGR in a vertical power MOSFET are experimentally

Manuscript received July 22, 2011. This work was supported in part by the NASA Electronic Parts and Packaging Program (NEPP), the Defense Threat Reduction Agency (DTRA) under IACRO# 10-4977I, IACRO# 11-4395I, and International Rectifier Corporation.

J.-M. Lauenstein, R. L. Ladbury, and K.A. LaBel are with NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), email: jean.m.lauenstein@nasa.gov, raymond.l.ladbury@nasa.gov, and kenneth.a.label@nasa.gov.

N. Goldsman is with the Dept. of Electrical Engineering, Univ. of Maryland, College Park, MD 20742 (USA), email: neil@umd.edu.

S. Liu, M. Zafrani, and P. Sherman are with International Rectifier Corporation, El Segundo, CA 90245 (USA), email: sliu1@irf.com, mzafran1@irf.com, and psherma1@irf.com.

J. L. Titus is with NAVSEA Crane Division, Crane, IN 47522 (USA), email: jeffrey.titus@navy.mil.

H. S. Kim and A. M. Phan are with MEI Technologies, Inc., work performed for NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), email: anthony.m.phan@nasa.gov and hak.s.kim@nasa.gov.

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 [4], which is validated for the power MOSFET used in this work.

II. Experimental Methods

A. Relative Importance of SEGR Mechanisms

A radiation-hardened 200V n-type vertical power MOSFET (VDMOS) was used for these experiments. Samples came from two wafers of the same diffusion lot. Heavy-ion test data were taken at the Texas A&M University Cyclotron Facility (TAMU). Fig. 2 shows a diagram of the irradiation test circuit. All samples were fully electrically characterized off-site; on-site prior to irradiation, a gate stress test was performed in which the gate leakage current was measured as a function of gate voltage at 0 Vds bias. Measurement equipment included a Keithley 2400 current-voltage sourcing and measurement instrument (SMU) for gate voltage supply and current measurement (< 1 nA accuracy) and either a Keithley 2400 or 2410 SMU for the drain voltage supply and drain current measurement. Samples were irradiated in air at normal incidence. 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 and to reduce effects of multiple proximal ion impacts [3, 4]. Vds was incremented in 5-volt steps; at each step, the sample was irradiated with a beam flux in the range of $1x10^4$ ions/cm^2/s to $2x10^4$ ions/cm^2/s, until either the sample failed or a fluence of $3x10^5$ ions/cm^2 was reached. A post-irradiation gate stress (PIGS) 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 during the run or following the PIGS test. Three to four samples per ion beam condition were irradiated at the -10 Vgs bias.

Six monoenergetic ion beams were 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. The ion LET versus penetration depth in silicon is plotted in Fig. 3; as shown in this figure, the epilayer region extends from 5 μm to 31 μm beneath the surface of the die. 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 [5, 6]. These values do not consider energy straggling effects as the ion passes through both air and the device overlayers. The reader is referred to a recent study quantifying these effects as a function of initial ion energy [7].

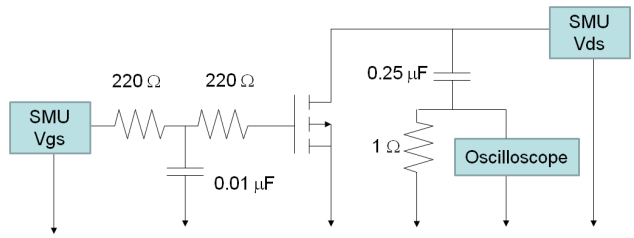

Fig. 2. Diagram of irradiation test circuit.

B. Verification of the Titus-Wheatley Formula for the Critical Gate Oxide Electric Field for SEGR

As a second part of this work, the critical gate bias necessary for SEGR at 0 Vds was found for six different combinations of ion species and energies (Table II in section III). Grounding Vds isolates the capacitive response [4] of the device. For each sample (same diffusion lot/wafers as the previous study) a strong negative gate bias (Vgs) of higher magnitude than the gate bias rating was applied and incremented in finer -0.5 V steps. At each step in Vgs, the sample was irradiated with a beam flux in the range of $5x10^3$ ions/cm^2/s to $2x10^4$ ions/cm^2/s, until either the sample failed or a fluence of $3x10^5$ ions/cm^2 was reached.

Table I. Ion Beam Properties for the 200V nVDMOS

Ion	Energy	Incident LET	LET at Oxide	Mean LET within 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

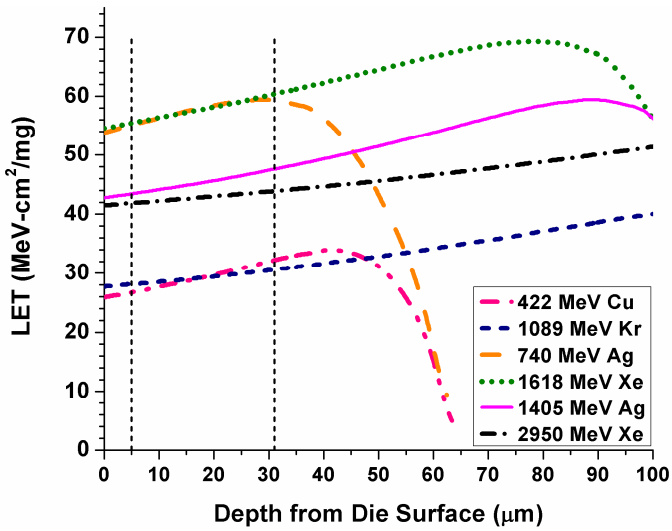

Fig. 3. Ion LET as a function of penetration depth. Vertical dashed lines demarcate the epilayer region.

III. Results

A. *Relative Importance of SEGR Mechanisms*

The results of these experiments suggest that both charge ionized in the epilayer and the ion atomic number are important parameters of SEGR failure, whereas the charge ionized in the substrate is of secondary importance. In this study, the threshold drain-source voltage 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 this way, the effect of ion LET was dampened to reveal any ion species effects on SEGR susceptibility.

1) $_{29}$Cu versus $_{36}$Kr (7.9 pC average total charge ionized in the device epilayer)

The first pairing consisted of irradiations by either 422 MeV copper (Z = 29) or 1089 MeV krypton (Z = 36). Three and four samples, respectively, were irradiated at a fixed -10 Vgs, with the threshold Vds for SEGR found by incrementing the Vds by 5 V 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 threshold Vds for the device tested has a normal distribution from part-to-part variability. The method of maximum likelihood [8, 9] was then employed to identify the mean (μ) and standard deviation (σ) best fitting our experimental data. To further account for our limited data set and hence the unknown extent of part-to-part variability, we use the standard deviation at the boundary of the 90% confidence level instead of this best fit value, using the χ-square value for 2 degrees of freedom (μ and σ). We can use the χ-square distribution in this way because the distribution of each likelihood estimator (μ_i and σ_i) tends toward a Gaussian with the best-fit value as the mean [10, 11].

Fig. 4 plots these best-fit means for the copper and krypton data, with error bars indicating one standard deviation from the mean at the boundary of the 90% confidence level (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 krypton ion. The difference in the mean Vds for SEGR is significant at the 90% CL. As shown in Fig. 4, we further characterized the effect of copper versus krypton ions by irradiating two additional samples with 422 MeV Cu, holding Vds at 130 V (a value within the failure range for krypton at -10 Vgs), 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.

2) $_{47}$Ag versus $_{54}$Xe (15.5 pC average total charge ionized in the device epilayer)

Examination of the LET versus depth curves for the copper and krypton ion beams (Fig. 3) reveals a small difference in the distribution of ionized charge within the epilayer, as well as a difference in total charge ionized within the heavily-doped drain substrate region. To better understand the influence of ion atomic number and ion LET on SEGR susceptibility, we tested a second pairing of ions. Both 740 MeV silver (Z = 47) and 1618 MeV xenon (Z = 54) ionize on average 15.5 pC in the device epilayer with similar distributions (Fig. 2). The same procedure as before was followed, with 4 samples irradiated with Ag and 3 with Xe. The results are plotted in Fig. 5. The data show a difference between the two ion species but this shift in the mean is not significant at the 90% confidence level. An additional sample was irradiated with silver at a fixed Vds of 50 V, but the Vgs bias required for failure was not significantly different than that for xenon under a 50 Vds bias.

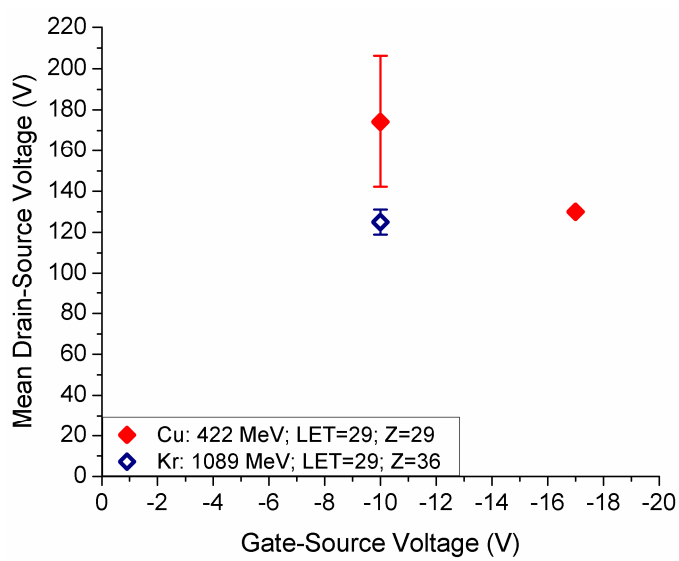

Fig. 4. Heavier Kr has lower threshold Vds for SEGR compared with lighter Cu, despite ionizing on average the same amount of charge in the epilayer. Error bars = 90% CL.

It is possible that high LETs reduce the significance of ion species effects or that a minimum necessary Vds for SEGR from Xe ions has been reached for the given Vgs bias. We pursue this latter hypothesis in section B below.

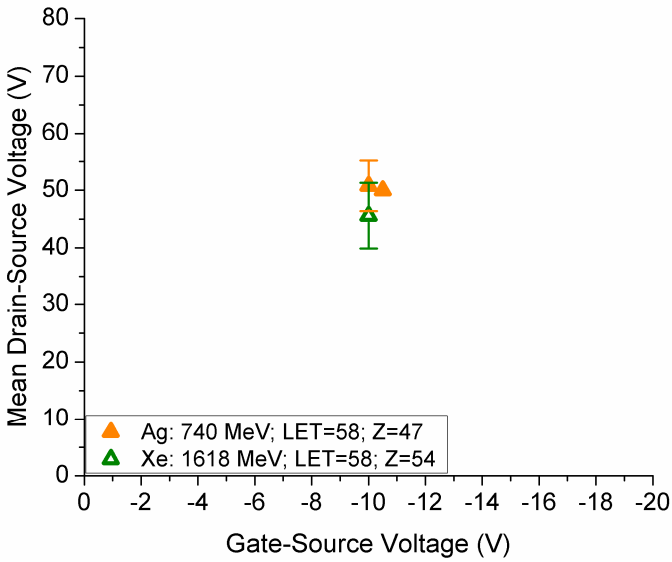

Fig. 5. The difference between Xe and Ag at high LET is not significant at the 90% CL.

3) $_{47}$Ag ionizing more charge in both the epilayer and initial 70 μm of the substrate than $_{54}$Xe

Lastly, the impact of ion species versus charge ionized in the epilayer and substrate regions was evaluated by comparing the bias necessary for SEGR under irradiation with 1405 MeV Ag to that under irradiation with 2950 MeV Xe. Fig. 3 shows that compared to the heavier xenon ions, the silver ions will ionize on average more charge throughout the epilayer thickness and also through the first 70 μm or more of the highly-doped drain substrate region. Irradiations were performed at -10 Vgs bias on 3 samples per beam condition following the same procedures as before. Fig. 6 shows that despite the silver ions having a higher average LET throughout the epilayer and into a substantial portion of the drain substrate region, a higher applied Vds was necessary for SEGR to occur at -10 Vgs with silver as compared to with the heavier species, xenon. This difference in failure threshold is significant at the 90% confidence level. This difference was further substantiated by irradiating 2 additional samples with 1405 MeV silver at a drain bias of 50 Vds, near the mean of the threshold for SEGR from xenon. Both of these additional silver samples experienced SEGR at -14 Vgs, having last survived at either -12 V or -13 V.

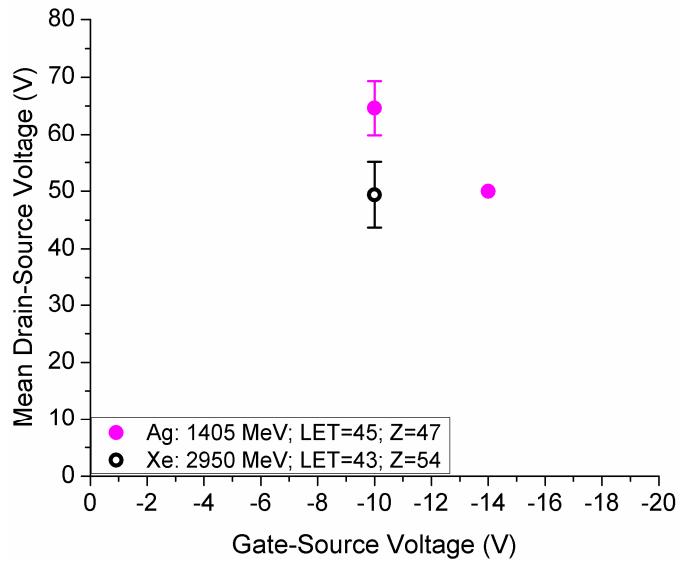

Fig. 6. The heavier ion species (Xe) ionizes less charge throughout the epilayer and a major portion of the substrate, yet still has a lower threshold bias for SEGR. Error bars = 90% CL.

B. Minimum Threshold Vds for SEGR Under $_{54}$Xe Irradiation at -10 Vgs

A plot of the threshold Vds for SEGR under the different silver and xenon irradiations as a function of ion atomic number highlights that for the same change in average total charge ionized in the epilayer, there is a larger change in threshold Vds for the silver irradiations than for the xenon irradiations (Fig. 7). Under a given Vgs bias and irradiation with a given ion species, there will be some minimum Vds bias necessary for SEGR to occur. That is to say, when the applied bias to the gate coupled with the ion interaction with the oxide are insufficient to cause gate rupture, the field in the oxide must be further raised by coupling a portion of the drain voltage across the oxide. For heavier ions such as xenon, less contribution from the drain bias will be necessary due to the stronger impact of the higher-Z ion on the critical oxide electric field necessary for rupture [4]. It is therefore expected that at a given gate bias, there will be a smaller variation in the threshold Vds at which SEGR occurs as a function of the higher-Z ion's total charge ionized in the epilayer, as Fig. 7 shows for xenon as compared with the lighter silver. Furthermore, there will be some minimum Vds below which SEGR will no longer occur regardless of the amount of charge the given ion generates. As the amount of charge that is ionized in the epilayer increases, the coupling of the drain voltage across the oxide strengthens; however, the effectiveness of the ionized charge to separate and create the transient increase in oxide electric field is dependent on the extent of the drift field in the epilayer when the ion strikes. Thus for a given applied gate bias, there will be a point at which increasing the energy that the particular ion species deposits in the epilayer will not further decrease the failure threshold Vds for SEGR

To determine whether this minimum failure threshold was reached under irradiation with 1618 MeV Xe (15.5 pC average charge ionization within the epilayer), two additional samples were irradiated with 1232 MeV Xe which ionizes on average 17.1 pC in the epilayer (Fig. 8). These irradiations were performed in vacuum at the Lawrence Berkeley National Laboratory 88" Cyclotron Facility's 10 MeV/amu beam tune, thereby avoiding energy straggle from beam energy degraders. As before, samples were biased at -10 Vgs and Vds incremented in 5-volt steps. Fig. 7 shows the 1232 MeV Xe yields the same failure threshold Vds for SEGR as found for 1618 MeV Xe, suggesting that the lack of significant difference between $_{47}$Ag and $_{54}$Xe ionizing on average 15.5 pC (Fig. 5) is due in part to having reached a minimum Vds for SEGR by Xe ions at -10 Vgs.

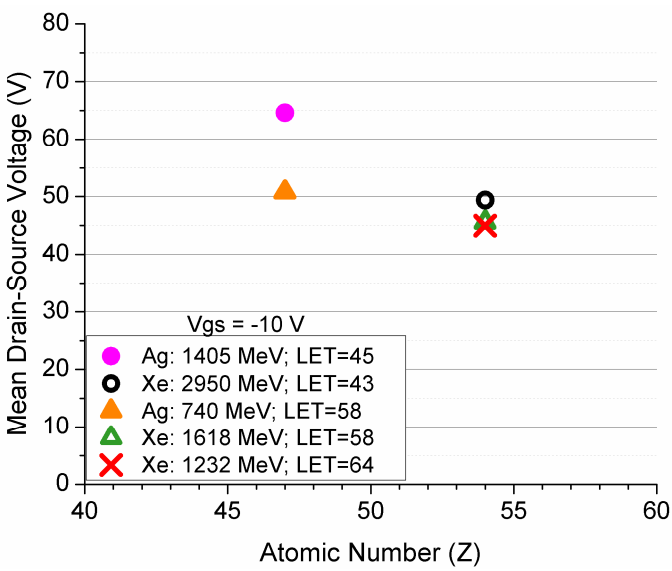

Fig. 7. Threshold Vds for SEGR as a function of ion species: increasing the LET of Xe ions above 58 MeV·cm2/mg did not lower the threshold.

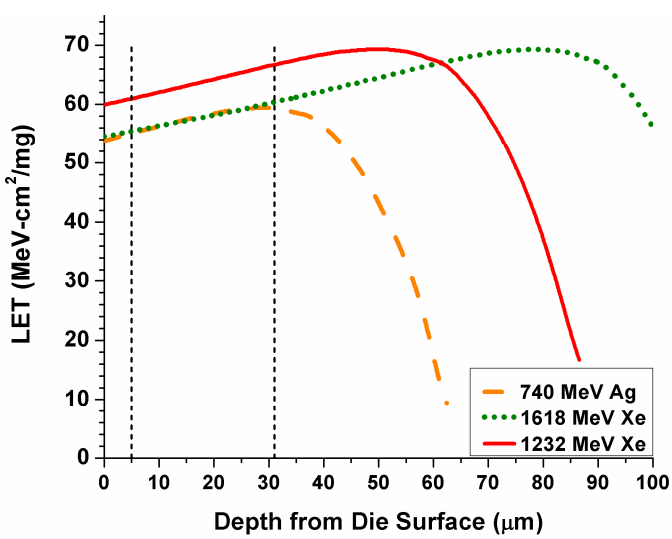

Fig. 8. Ion LET as a function of penetration depth, with higher-LET Xe shown.

When the drain-source voltage is grounded, the difference in the critical field necessary for gate rupture can be determined from the Titus-Wheatley semi-empirical formula [4]:

$$\mathrm{Ecrit}_{ox}\ (\mathrm{V/cm}) = \frac{V_{gs}\mathrm{crit}}{t_{ox}} = \frac{10^7}{1+Z/44}, \qquad (1)$$

where t_{ox} is the gate oxide thickness in cm and Z is the ion atomic number. This expression predicts that at 0 Vds, the difference in Ecrit_{ox} for silver (Z = 47) versus xenon (Z = 54) is 3 V/t_{ox}. We may expect that the minimum difference in threshold Vds from silver and xenon ion irradiation at -10 Vgs would therefore be about 3 V, barring differences in effectiveness of coupling the drain voltage to the gate oxide. Detection of this minimum difference may not be possible due to part-to-part variability, and would otherwise require a very large sample size and smaller step size in Vds.

C. Validation of the Titus-Wheatley Formula (1) for the Isolated Gate Oxide Response of this 200 V nVDMOS Test Device

The Titus-Wheatley formula was developed through experiments performed more than a decade ago and has not to our knowledge been validated since that time. In order to use this formula to gain insight into the results of Figs. 4-7, we believe it is important to verify (1) for the test device used in this work to confirm the Z dependence and determine the appropriate fitting parameter (equal to 44 in (1)). Table II shows the 6 beam conditions used. In all cases, gate rupture occurred during irradiation, resulting in a sudden gate leakage current increase to the 1 mA supply current limit.

Table II. Ion Beam Properties for Irradiations Performed at 0 Vds

Ion Beam Characteristics			
Species *Z*	Energy *MeV*	LET *MeV·cm²/mg*	Range *μm*
29	422	25.8	64.5
29	825	18.5	145.4
36	1089	27.7	140.4
47	740	53.7	64.3
47	1405	42.5	124.8
54	1618	54.6	119.0

The critical voltage for gate rupture is plotted as a function of ion species (red diamonds, Fig. 9). For comparison, the measured gate oxide electrical breakdown voltage for this lot is -67 ± 4 V. In fitting these data, we initially make no assumptions regarding the best-fit model. A two-parameter reciprocal function of the form y=A/(1+Bx) yields a better fit than a simple linear function or a power-law model according to the adjusted R^2 value (0.9671 versus 0.9658 or 0.9627, respectively). The R^2 value gives the fraction of the variability in the data not captured by the model used to fit the data. Its

value therefore ranges from 0.0 to 1.0, demonstrating the goodness of fit. The adjusted R^2 accounts for the degrees of freedom in the model, since the R^2 value will increase simply due to the addition of model parameters [10]. Notably, the best-fitting model to the data in this study is the form of the Titus-Wheatley formula (1) and for these data results in the following fitted function:

$$\text{Vcrit} = -84/(1 + Z/49.5)\,, \qquad (2)$$

and is plotted in Fig. 9 (red dot-dash line). Comparing the numerator in (2) to its analogue in (1), this fit suggests a gate oxide thickness of 84 nm. Because this value is too low, we fix the second parameter, B, to 1/44, that of the Titus-Wheatley formula; we then find the numerator yielding the best fit to the data. This fit, shown as a blue dotted line in Fig. 9, yields an accurate thickness for this device. Fixing the second parameter to 1/44 reduces the adjusted R^2 value only minimally, from 0.9671 to 0.9650.

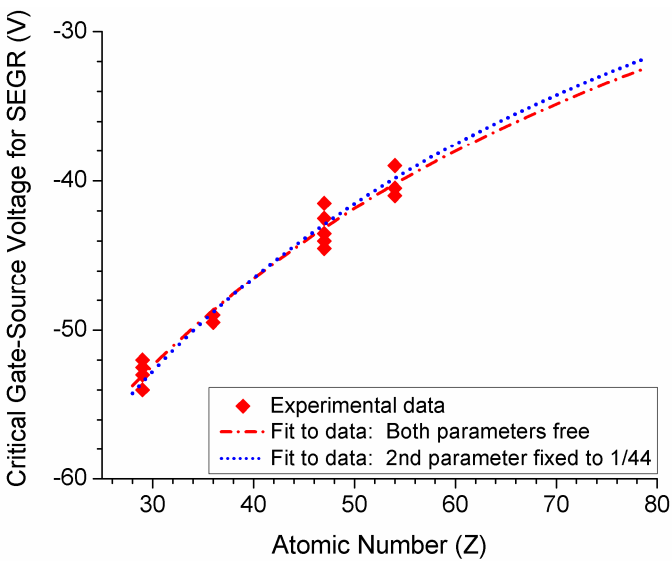

Fig. 9. Critical Vgs for SEGR at 0 Vds as a function of ion species. Data are fitted to the reciprocal function y=A/(1+Bx).

IV. Discussion

A. *Mechanisms*

Past studies have suggested that SEGR susceptibility depends on ion atomic number as well as the ion LET or total charge ionization [4, 12]. To our knowledge, this study is the first to evaluate similar charge deposition throughout the silicon epitaxial layer for two different ion species in order to examine the impact on SEGR of different ion species. This work suggests that ion atomic number cannot be neglected when considering SEGR risk on orbit.

As shown in Figs. 4 – 6 for all three pairings of ions the heavier ion resulted in a lower mean Vds threshold for SEGR than did the lighter ion, despite the lighter species ionizing on average the same or even more charge in the drain epilayer. This difference was not significant for the silver versus xenon ions when their average LET in the epilayer was 57.8 MeV·cm^2/mg, but became significant at the 90% confidence level when the average LETs were 45.4 MeV·cm^2/mg and 42.8 MeV·cm^2/mg, respectively. Fig. 7 demonstrates that this lack of significance at the higher average LET may be due to a minimum Vds threshold being reached for xenon irradiation at -10 Vgs. The sample size and Vds bias step size in this study precludes the ability to detect with significance the expected less than 5-volt difference in the minimum failure thresholds for silver versus xenon. To examine the results of this study further, we first identify the sources of deviation from the mean SEGR threshold drain biases.

The results presented in Figs. 4 – 6 have large error bars that represent the 90% worst-case upper bound on the standard deviation for the distribution of failures. The small sample size, part-to-part variability, the Vds step-size interval, bond-wire shadowing effects [7, 13], energy straggling [7], and the Poisson nature of the failures all contribute to this uncertainty in the best-fit mean. 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 single wafer diffusion lot for the samples, a Vds step increment of only 2.5% of the rated BVdss, a small bond-wire cross-section, and a high fluence at each beam run.

The samples in this study have a single wire bond to the source that extends approximately 0.5 cm over the active die region. The wire measures 20 mil in diameter, giving it a cross-section of 0.0254 cm^2. Fifteen percent of the 0.17 cm^2 die is therefore shadowed by the bond wire. If we assume that the gate region is 30% of the die area, the impact of the bond wire shadowing is further reduced. Ion strikes to the center of the bond wire would stop the ion; however, passage near the edge of the wire width would only slow down the ion. Higher-energy test ions can therefore lose energy to the bond wire but ionize on average higher total charge in the epilayer due to this energy loss [7, 13]. Conversely, the lower-energy Ag and Cu ions shown in Fig. 3 would ionize less charge within the epilayer since the Bragg peak would move from the epilayer/substrate interface into the epilayer itself. In this way, bond-wire shadowing effects would enhance the likelihood of the heavier ions ionizing more charge in the epilayer than the lighter ions to which they are compared, skewing the results toward the heavier ion yielding a lower threshold bias for SEGR than the lighter ion species. This skewing would be due to charge ionization differences, not true ion species effects.

The probability of this occurrence must therefore be examined. Using the OMERE Equivalent LET software [5] and SRIM [6], we find that a loss of up to 860 MeV to the aluminum bond wire will cause krypton ions to ionize more charge in the epilayer than that of the copper ions to which krypton is compared. This energy loss translates into passage of a Kr ion through up to 96 µm of the Al wire thickness, or 1.8 % of the wire diameter. For a single beam run of 3 x 10^5

ions/cm^2, an average of 41 ions (0.014 %) would strike the gate region and ionize on average more charge in the epilayer than those not losing energy to the bond wire. A similar analysis of the 2950 MeV Xe ions suggests that 0.038 % of the Xe ions would strike the gate region and ionize on average more charge in the epilayer than would the 1405 MeV Ag ions. These values are conservative in that we have not accounted for the curvature of the bond wire rendering a smaller portion of the wire thin enough to effectively slow down the incident ion.

The variability in the threshold Vds for SEGR was largest for the lightest ion tested. The 422 MeV Cu ions were obtained by passing the ion beam through a 2.8 mil aluminum degrader. The use of a degrader results in a greater spread in the energy range of the resulting ion beam due to energy straggling as ions pass through the degrader material. The spread of energies for this copper beam was examined using the Monte Carlo routine, TRIM, within the SRIM package [6]. Although the standard deviation about the mean energy was small (2.7 MeV), the range of ion energies extended below 220 MeV to above 432 MeV. At energies below 360 MeV, copper can ionize 8.5 pC or more (up to 8.75 pC), as opposed to the average 7.9 pC in the epilayer region. The probability of such a lower-energy copper ion striking the gate region of the sample is small, but not zero: of the ions striking anywhere on the die during a single beam run, the Monte Carlo results suggest 0.02%, or 10 ions given the die size of our samples, would have energies below 360 MeV; of these 10 ions, about 30%, or 3 ions, would strike the gate region.

The Titus-Wheatley formula (1) which was verified for the device used in this study indicates that the ion atomic number is the primary variable affecting the electric field required for gate rupture. In Figs. 4 and 6, the additional Vgs bias required to reduce the threshold Vds of the lighter ion to that found for the heavier ion is similar or slightly higher than the difference in V_{gs}crit determined from Fig. 9. In Fig. 4, a 6-volt to 7-volt increase in Vgs magnitude was required for Cu ions to induce SEGR at the 130 Vds failure threshold determined for Kr, as compared to a 4.6-volt difference predicted by (1) for a 0 Vds bias. In Fig. 6, a 3-volt to 4-volt increase in Vgs magnitude was required for Ag ions to induce SEGR at the 50 Vds threshold for Xe, compared with the 3-volt prediction from (1). In order to fully understand the differences, a statistical study would be needed of the range in Vgs values for the different ion species at the respective Vds biases. It is conceivable that the ion species effect at non-zero Vds may include both the gate oxide response and the epilayer mechanisms of SEGR, the latter mechanism occurring through track structure effects on the extent of drain voltage appearing across the gate oxide.

Charge ionized within the highly-doped drain substrate did not have nearly 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 (Fig. 6). Only charge in the initial few μm of the heavily-doped substrate (the transition region) would be expected to contribute to the transient electric field. In the remainder of the substrate there is only a minimal electric field, and charge would be collected primarily by slower diffusion processes. This substrate charge would also undergo higher recombination prior to collection. These considerations suggest that the important ion beam characteristics for inducing SEGR are the total energy deposited in the epilayer (including the epi/substrate interface region), and the ion atomic number.

B. Implications

The work presented here has SEGR hardness assurance implications. Both charge ionized in the epilayer and the ion atomic number are important parameters of SEGR failure. These ion species effects should be incorporated into efforts to bound the on-orbit risk of SEGR, as well as the ion angle of incidence (not studied here). LET (or average LET) alone is not the appropriate metric for defining the hazardous environment; a fuller description of the mission-specific radiation environment (*e.g.* Fig. 10) to reveal the details involved in the primary SEGR mechanisms of ion atomic number and energy deposition within the epilayer and epi/substrate transition region.

At the high energies of galactic cosmic rays, for a given incident LET a heavier ion has a longer penetration range. In addition, hard nuclear inelastic reactions that can occur at high energies have a much lower cross section than coulombic interactions; this fact combined with the strong angular dependence of SEGR significantly diminishes the contribution of nuclear spallation events to the SEGR failure rate. The SEGR hazardous environment can therefore be defined in more familiar terms of differential flux vs. incident LET vs. Z (Fig. 11), to capture both ion species and energy effects on SEGR susceptibility. For a given set of test conditions a test result divides the space radiation environment into 3 regions: ions known to be safe, ions known to pose a threat, and a third category where the threat remains indeterminate, *e.g.* either the atomic number or LET exceed that of the test ion. As an example, using the test results in Fig. 4 for the Kr test conditions, the flux in Fig. 11 for geostationary orbit is divided into ions whose threshold Vds would be lower (known threat), higher (known to be safe), and regions of unknown threat (the threshold Vds for SEGR cannot be determined from the test data alone). We have not considered the angle of incidence of the ion on the device. SEGR is very angularly-dependent, such that susceptibility decreases as the angle at which the ion strikes the top or bottom surface of the die becomes more acute. This angular response must be incorporated into efforts to define a failure rate.

In Fig. 10, it is clear that the flux of ions as heavy as or heavier than krypton (Z=36) is much lower than for lighter ion species. The impact of these heavy ions can be assessed by comparing a worst-case SEGR failure rate to the intrinsic

failure rate for the device. A worst-case (upper-bound) SEGR failure rate can be calculated by integrating the flux composing the known and unknown threat regions in Fig. 11. We use the following assumptions: 1) the vulnerable die area for SEGR is 30% of the total die area, 2) the device is biased in the off-state 50% of the time, at the threshold Vds for SEGR under krypton irradiation with surface-incident LET of 27.7 (the parameters used to define the safe/threat regions in Fig. 11), and 3) the angle of vulnerability for SEGR includes any ion strikes to the front or back side of the device at angles up to 30° from normal incidence. The worst-case SEGR failure rate can then be calculated from the following equation based on [14]:

$$\mathrm{Rate}_{\mathrm{UB}} = \Phi_{\mathrm{UB}} \cdot \mathrm{A} \cdot 4\pi(1-\cos(\theta)) \cdot f \qquad (2)$$

where Φ_{UB} is the hazardous flux in ions/(cm$^2\cdot 10^6$ hrs), A is the vulnerable area of the die in cm^2, θ is the angle of vulnerability, and f is the fraction of time that the device is biased in the off state. With the assumptions made above, the worst-case failure rate is 6.04 failures per million hours. For comparison, the intrinsic device failure rate can be estimated using MIL-HDBK-217F-Notice 2, section 6.4 [15]. For this calculation, we assume an 85 °C operating temperature, the maximum power dissipation for the device at this temperature (78 W), and a quality factor for a JANTX part. The intrinsic failure rate is then 0.144 failures in one million hours. These estimates suggest that SEGR may occur from ions as heavy as or heavier than krypton at a worst-case rate that is 42 times that of the intrinsic failure rate.

It may be more appropriate to reduce the contribution from the region of unknown threat due to ions with Z ≥ 36 (see Fig. 11) by including only the flux for ions with incident LETs of at least half that of the test ion LET (*i.e.*, LETs greater than 13.9), as inclusion of this entire unknown threat region is clearly overly conservative [16]. Reducing the contribution of flux in the unknown threat region in this way results in a worst-case SEGR failure rate that is still 32 times that of the intrinsic failure rate. These high failure rates drop rapidly as the LET of krypton is increased: if we again only include the flux for ions with incident LETs of at least half that of the test ion LET, then defining the SEGR failure threshold for this device with krypton ions having a surface-incident LET of 32.5 MeV·cm^2/mg reduces the calculated failure rate to that of the intrinsic rate of 0.144 failures in 10^6 hours.

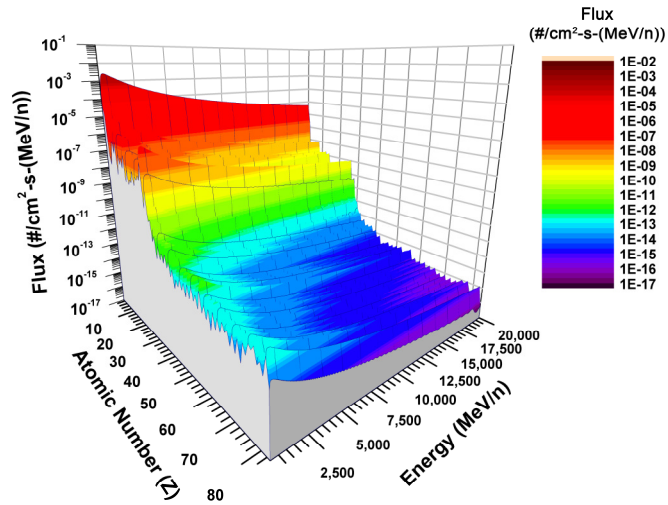

Fig. 10. The galactic cosmic ray environment at geostationary orbit during solar minimum behind 100 mils Al shielding is shown with LET expanded into its underlying components of ion atomic number and energy.

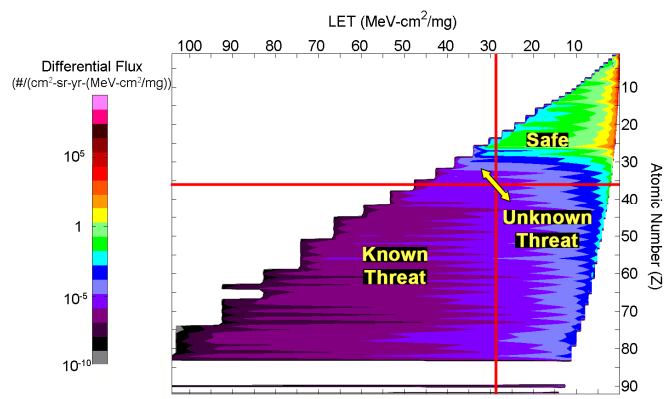

Fig. 11. Geostationary orbit environment defined by flux as a function of LET and Z. Plot is divided into hazard categories according to the test results in Fig. 3 for the Kr test conditions.

V. Conclusion

This work focuses on the complete SEGR mechanism, assessing the relative importance of the heavy-ion interaction with the oxide, the charge ionized in the epilayer, and the charge ionized in the drain substrate, on inducing SEGR. To our knowledge, this study is the first to evaluate similar charge deposition throughout the silicon epitaxial layer for two different ion species in order to examine the impact on SEGR of different ion species. The results indicate that both charge ionized in the epilayer/epi-substrate interface and the ion atomic number are important parameters of SEGR failure, while the charge ionized in the substrate is at most of secondary importance. Although not examined here, the ion angle of incidence is also of primary importance given the omnidirectional flux of ions in space.

These findings reinforce the inadequacy of the LET metric for power MOSFET radiation hardness assurance approaches. A fuller description of the heavy-ion environment such as ion flux as a function of both LET and atomic number would account for the parameters addressed in this work that are of primary importance for SEGR. On-orbit failure rate prediction methods that more accurately bound the failure rate for a given off-state bias will provide rationale for using a larger portion of a device's rated bias range. Such methods will guide the selection of accelerator beam species and energies suited for a given device and mission that do not yield overly conservative single-event response curves.

Further research is needed to study the relative importance of the ion atomic number and the energy deposition in the epilayer at 0 Vgs bias, which is often used in power MOSFET space applications.

ACKNOWLEDGMENT

The authors thank Martha O'Bryan, Donna Cochran, Donald Hawkins, and Stephen Cox of NASA-GSFC for technical assistance, and Leif Scheick of NASA/JPL and Christian Poivey of ESA for helpful discussions.

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