Interpreting Space-Mission LET Requirements for SEGR in Power MOSFETs

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Abstract—A TCAD simulation-based method is developed to evaluate whether derating of high-energy heavy-ion accelerator test data bounds the risk for single-event gate rupture (SEGR) from much higher-energy on-orbit ions for a mission linear energy transfer (LET) requirement. It is shown that a typical derating factor of 0.75 applied to a single-event effect (SEE) response curve defined by high-energy accelerator SEGR test data provides reasonable on-orbit hardness assurance, although in a high-voltage power MOSFET, it did not bound the risk of failure.

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

I. INTRODUCTION

POWER MOSFETs are used ubiquitously in space flight missions, due in part to their simpler drive circuitry and high-speed switching. Two potentially catastrophic failure mechanisms create a radiation hardness assurance challenge for these devices when biased in the off-state: Single-event gate rupture (SEGR) and single-event burnout (SEB). Over time, successful process-level methods for reducing SEB susceptibility have been implemented [1]-[4] elevating the profile of SEGR as a continued concern in radiation-hardened vertical power MOSFETs. In part due to the severity of SEGR consequences and in part due to the difficulty of accurate SEGR rate estimation, SEGR mitigation methodologies emphasize risk avoidance, using heavy-ion accelerator tests to define safe operating conditions for a surface-incident linear energy transfer (LET). This “safe-operating area” (SOA) within which the device may be biased without experiencing SEGR [5] is then often derated by a prescribed factor to ensure low risk of SEGR. A key to this methodology is the assumption that operating the power MOSFET within the resulting derated SOA will avoid SEGR from heavy ion strikes having the mission incident LET requirement or below.

The possibility of false assurance resulting from LET-based SEGR hardness requirements without consideration of ion energy was first identified by Titus, et al. in 1996 [6]. Since then, numerous studies [7]-[11] have demonstrated the importance of testing with ions whose range fully penetrates the sensitive epilayer(s), as these ions more accurately reflect the high-energy space radiation environment and yield a reduced SOA for a given surface-incident LET. In addition to ion energy, SEGR susceptibility is a function of ion species, with heavier ions reducing the threshold bias condition for SEGR [12]-[13]. Whereas a new test method was proposed to identify the worst-case SOA for a given ion species [10], most mission radiation requirements for SEGR are still specified in terms of surface-incident LET. Moreover, terrestrial SEGR tests at a given surface-incident LET are limited by the small number of ion species and energies available at heavy-ion accelerators. In comparison, the on-orbit radiation environment is composed of all of the naturally-occurring elements with peak fluxes at nearly GeV/nucleon energies [14]. The term “safe-operating area” therefore can be misleading in that there may be combinations of ion species and energies that induce gate rupture at biases within the specified device SOA. In this paper, we will refer to the traditional SOA as the “SEE response curve” for a given ion species and energy, and reserve the SOA nomenclature for the region defined by applying a derating factor to the SEE response curve (the region of lesser-magnitude biases under the resulting derated SEE response curve).

The primary objective of this study is to examine whether typical derating of high-energy heavy-ion accelerator test data bounds the risk for SEGR from higher-energy on-orbit ions with the mission LET requirement. The general-purpose Technology Computer Aided Design (TCAD) device simulator, Synopsys Sentaurus Device [15], is used to evaluate the common derating practice in both a radiation-hardened 200V nVDMOS and a commercial 500V pVDMOS structure. Each transistor model is calibrated either to low-energy heavy-ion accelerator beam data provided in the vendor datasheet, or to a subsection of higher-energy data provided in a radiation test report [16], respectively. For the 200V nVDMOS, higher-energy accelerator beam data are obtained to validate the model and to provide the SOA to be evaluated. Comparison of these data with simulated data for the same ions and energies...
demonstrate the predictive capability of the simulation model, increasing confidence in the methodology.

Lastly, SEGR hardness assurance is explored in the context of the heavy-ion space environment. The critical next steps are identified to refine the ability to more tightly bound the on-orbit risk of SEGR.

II. METHODS

A. Experimental Data

A radiation-hardened 200V n-type vertical power MOSFET (VDMOS) is one of the devices selected for this study. The device datasheet has a single-event effect response curve defined by low-energy (~4 MeV/u) heavy ions whose Bragg peak fell within the sensitive epilayer volume. Heavy-ion test data were taken at the Texas A&M University Cyclotron Facility (TAMU) using higher-energy ion beams (~12 MeV/u) having similar surface-incident LETs as those used to define the SEE response curve in the vendor datasheet for the part.

All samples were electrically characterized on-site at TAMU for gate threshold voltage (Vgs), drain-source breakdown voltage (BVdss), and gate leakage current (Igss). Measurement equipment included a Keithley 2400 for gate voltage supply and current measurement (< 1 nA accuracy), a HP34401A digital multimeter placed across a 50Ω resistor at the drain node to determine the drain current, and an Agilent 6035A power supply for the drain voltage. Samples were irradiated in air; beam characteristics at the surface of the die, gate bias, and sample size are provided in Table I. Surface-incident LET is determined using the SRIM-based Seuss software provided by TAMU. For each sample, the appropriate gate bias (Vgs) was applied and the drain-source voltage (Vds) incremented in 5 V steps. At each step in Vds, the sample was irradiated with a beam flux of 5x10^3 ions/cm²/s until either the sample failed or a fluence of 5x10^5 ions/cm² was reached. A post-irradiation gate stress test was then performed; if the gate leakage current was still within vendor specification, Vds was incremented and the process repeated. SEGR was defined as the gate current exceeding the vendor specification of 100 nA maximum Igss.

### Table I

<table>
<thead>
<tr>
<th>VDMOS</th>
<th># of Samples</th>
<th>Vgs Bias (V)</th>
<th>Ion Species</th>
<th>Ion Energy (MeV)</th>
<th>Ion Range (µm)</th>
<th>LET (MeV·cm²/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200V</td>
<td>2</td>
<td>0</td>
<td>Kr</td>
<td>1012</td>
<td>131</td>
<td>28.1</td>
</tr>
<tr>
<td>200V</td>
<td>3</td>
<td>-12</td>
<td>Kr</td>
<td>1012</td>
<td>131</td>
<td>28.1</td>
</tr>
<tr>
<td>200V</td>
<td>3</td>
<td>0</td>
<td>Ag</td>
<td>1362</td>
<td>126.8</td>
<td>41.3</td>
</tr>
<tr>
<td>200V</td>
<td>3</td>
<td>-12</td>
<td>Ag</td>
<td>1362</td>
<td>126.8</td>
<td>41.3</td>
</tr>
</tbody>
</table>

B. Simulated Data

The general-purpose technology computer-aided design (TCAD) device simulator, Synopsys Sentaurus Device [15], is used to simulate SEGR. For the 200V radiation-hardened nVDMOS, the transistor structure is developed using standard doping and geometry profiles for a medium-voltage device, and is calibrated to the SEE response curve for 4 MeV/u heavy-ion accelerator beam data provided in the vendor datasheet. In addition, a 500V commercial pVDMOS TCAD model is developed from a subsection of existing 25 MeV/u TAMU data and scanning electron microscope images provided in a NAVSEA-Crane radiation test report [16]. Small adjustments in the geometry and doping were made to calibrate the models. A brief analysis of the impact of adjustments to the drain neck width or epilayer doping concentration is given in section IV.

The device simulator solves the Poisson, charge-continuity, and current equations in the silicon using finite-element techniques. Three-dimensional fidelity was obtained using a 2-dimensional cylindrical coordinate system since all ions were simulated to strike at the center of the drain neck region at normal incidence. Simulated ion strikes reflect the changing ionizing energy loss along the length of the ion track as calculated with SRIM [17]. A Gaussian radial distribution with characteristic radius of 50 nm is used until the actual track radius determined from the Fageeha model [18] falls below 50 nm; this calculated radius is then substituted. The finite time for the ion to pass through the thicker 500V device is accounted for by widening of the track radius into a conical shape as follows. The time for the ion to pass through the modeled device was approximated by calculating the ion velocity from its incident energy, then multiplying the inverse of this velocity by the thickness of the modeled silicon region. Simulations were then performed with a uniform characteristic radius of 50 nm. The hole density near the silicon-silicon dioxide interface was plotted as a function of distance from the ion track core both at the time of the ion strike and at the calculated time for the ion to pass through the modeled device. The difference in the distance at which the hole density reached its background level was then used as the ion-specific track characteristic radius at the Si/SiO₂ interface. This characteristic radius was linearly reduced to 50 nm at the end of its passage through the silicon. It is important to ensure that the mesh spacing is small enough to permit such a comparison of hole density distributions.

The physics models governing charge transport include concentration-dependent Shockley-Read-Hall (SRH) and Auger recombination; bandgap narrowing and Fermi-Dirac statistics; velocity saturation and impact ionization driven by the gradient of the quasi-Fermi levels; and impurity and carrier-carrier scattering. Determination of SEGR was made from the simulated peak electric field across the oxide using the Titus-Wheatley semi-empirical expression for the critical field for breakdown (Ecrit) based upon the ion atomic number (Z) [12]:

\[
E_{\text{crit}} (\text{V/cm}) = 1 \times 10^{7} / (1 + Z/44)
\]

Electrical stress measurements of the pristine oxide cannot be used since the interaction of the heavy ion with the oxide
reduces $E_{\text{crit}}$ [19]-[21]. This expression yielded good agreement between simulated and experimental SEGR data in a previous study [22].

III. EXPERIMENTAL RESULTS

Heavy-ion tests of the 200V nVDMOS reveal that near the typical mission-requirement LET of 40 MeV·cm²/mg, the single-event response curves defined by 12 MeV/u TAMU test data is reduced from that of the 4 MeV/u data provided in the vendor datasheet (Fig. 1). This finding is in keeping with prior studies of energy effects on SEGR susceptibility in power MOSFETs [7]. For the lower-surface-incidence LET of 28 MeV·cm²/mg, the SEE response curves defined by 4 MeV/u Cu and 12 MeV/u Kr are comparable, though the -12 Vgs Kr data suggest a faster roll-off of the SEE response curve than is detectable with the vendor Cu data set. Note that for consistency with TAMU LET calculations, the vendor LETs indicated in Fig. 1 have been recalculated with SIRIM [15] and thus differ slightly from their datasheet values determined at Brookhaven National Laboratory.

When typical derating factors of 0.75 Vds and 0.6 Vgs are applied to the vendor’s 41 MeV·cm²/mg data, the 12 MeV/u Ag data at 0 Vgs fall just above the derated 4 MeV/u Br SEE response curve, leaving no margin for factors such as part-to-part variability.

IV. SIMULATION RESULTS

A. 200V Radiation-Hardened nVDMOS

Simulation studies were performed to evaluate whether typical derating of the higher-energy TAMU data will bound the risk of SEGR on-orbit. As shown in Fig. 2, the model of the 200V nVDMOS was successfully calibrated to the vendor data. In this figure and subsequent SEE response curve plots, error bars on experimental data reflect measurement uncertainty, and simulation error bars reflect the uncertainty in the oxide field required for SEGR. Without adjustment, the model predicted the higher-energy experimental data taken in this study (Fig. 3), demonstrating the predictive capability of the method.

The ion species used to develop the Titus-Wheatley expression (1) range from Z=28 (Ni) to Z=79 (Au). With this expression, the SEE response curve for ions up to Z=79 can therefore be extrapolated from the model. Fig. 4 plots the simulation results of 68 MeV/u Au, showing that the SEE response curve for Au ions with a surface-incident LET of 40 MeV·cm²/mg lies just outside the SOA defined from derating the TAMU data. Operating within the SOA defined from derating the higher-energy TAMU data may therefore prevent SEGR for ions as heavy as Au, although there is minimal margin for other variables such as part-to-part variability and aging effects. A 0.75 derating factor applied to the SEE response curve defined by TAMU data is appropriate for this device (Fig. 4) when the relative flux of heavier species is considered.

B. 500V Commercial pVDMOS

Simulation studies were next performed to evaluate whether typical derating of the high-energy TAMU data bounds the risk of SEGR on-orbit in a higher-voltage commercial p-channel device. Only TAMU data are available for this device; the model was therefore calibrated to the 0 Vgs heavy-ion test data. Accounting for the finite time for the ion to pass through the device was essential. The predictive capability of the model was verified by comparing the higher-magnitude Vgs simulated data with that in the radiation test report (Fig. 5).

Next, a 68 MeV/u Au ion strike was simulated. Fig. 6 shows this data against both the derated experimental Xe and simulated Xe SEE response curves. The simulated response curve for the Au ions falls just inside the derated Xe SEE response curves. A 0.75 derating factor applied to the SEE response curve defined by 21 MeV/u TAMU data therefore does not bound the risk of SEGR from 40 MeV·cm²/mg (surface-LET) ions for this device.

C. GCR Environment

As demonstrated in the previous results, the LET metric obscures environment details important to evaluating SEGR susceptibility and thus the maximum off-state biases at which a given power MOSFET may be operated safely. In Fig. 7A, the ion flux as a function of species and energy, as calculated with the ISO15390 galactic cosmic ray model [23] for geostationary orbit at solar minimum, is shown. Figs. 7B-7D identify the safe portion of the ion flux for SEE response curves defined by Br, Ag, or Au ions with an incident LET of 40 MeV·cm²/mg. Also identified is a region of uncertainty: Combinations of heavier species with higher energies (lower LETs), or lighter species with lower energies (higher LETs), than that used to define the SEE response curve will add to the SEGR hardness-assured portion of the spectra. Table II quantifies the remaining potentially hazardous flux revealed in Figs. 7B-7D, providing a conservative lower and upper bound based upon exclusion/inclusion of these regions of uncertainty (down to an LET of 20 MeV·cm²/mg for the region of higher-Z ion flux). SEGR is highly angularly dependent such that susceptibility under a particular bias condition decreases with increasing off-normal angle of incidence to the surface of the device. Flux values in Table II are therefore presented as per-steradian without any assumption regarding the change in hazardous flux as a function of angle. For comparison with the values in Table II, the integral flux for all species with LET $\geq 40$ MeV·cm²/mg is 1.40x10⁻³ ions/(cm²·yr·sr). Narrowing of these ranges of flux will require further studies to identify the relative importance of ion species versus energy deposition, as well as the angular response; the precise relationship between these effects will be device-dependent.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>UPPER AND LOWER BOUND OF HAZARDOUS FLUX (IN IONS/(CM²·YR·SR) BASED UPON TEST ION SPECIES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z=35$ (Br)</td>
<td>$Z=47$ (Ag)</td>
</tr>
<tr>
<td>Lower</td>
<td>1.37x10⁻³</td>
</tr>
<tr>
<td>Upper</td>
<td>9.79x10⁻³</td>
</tr>
</tbody>
</table>
D. Drain Geometry and Epilayer Doping Effects

The models in this study were calibrated by adjusting the device geometry and doping profile. Fig. 8 shows a cartoon cross-section of a VDMOS under normal operation; the area of the drain between the body implants is called the drain neck region. Table III demonstrates the effects of changes to the drain neck width and epilayer doping on the transient peak electric field across the oxide. In this table, the values of the peak field resulting from krypton, xenon, or gold ion strikes are shown for the 500V pVDMOS model. The total drain neck width is then narrowed by 2 µm, or widened by 2 µm or 4 µm, and the percent change in the peak electric field across the oxide is noted for each ion. Similarly, the epilayer doping concentration is increased or decreased from the calibrated model value by about 30%. In each case, the simulations were run under 0 Vgs and at the Vds at which SEGR occurred for the given ion species and energy (see Figs. 5-6).

Changes in the drain neck width have a greater impact on the oxide transient electric field than do adjustments to the epilayer doping. As reported previously [22], a narrower drain neck region results in a lower peak electric field forming across the oxide. Of the three ions simulated, the transient field resulting from krypton is most sensitive to changes in the drain neck width. Experimentally, samples irradiated with krypton showed greater part-to-part variability of the threshold drain voltage at which SEGR occurred [16], suggesting that the lower LET (and hence less charge ionization in the epilayer) may be responsible for this sensitivity. Simulations in this study demonstrated a weaker relationship between Vds and the threshold drain voltage at which SEGR occurred [16], suggesting that the lower LET (and hence less charge ionization in the epilayer) may be responsible for this sensitivity. Simulations in this study demonstrated a weaker relationship between Vds and the peak transient field across the oxide for 22 MeV/u xenon than for 21 MeV/u xenon or higher-energy gold.

Significant adjustments to the epilayer doping concentration had only a small effect on the peak transient electric field. Increasing or decreasing the doping concentration generally produced a slight increase or decrease, respectively, in the peak electric field. In contrast, these adjustments strongly affect the drain-source breakdown voltage (BVdss). The higher doping concentration shown in Table III reduced the breakdown voltage to below the rated 500 V. The epilayer doping profile should therefore be adjusted to fit the measured BVdss. The relationship between BVdss, epilayer thickness, and doping concentration is detailed in [24].

TABLE III. PERCENT CHANGE IN OXIDE PEAK ELECTRIC FIELD AS A FUNCTION OF DRAIN GEOMETRY AND DOPING (UNDER APPLIED VGS = 0 V)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Vds (V)</th>
<th>Voxide (V/cm)</th>
<th>Eox (V/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kr</td>
<td>-450</td>
<td>5.3 x 10^6</td>
<td>-1.0</td>
</tr>
<tr>
<td>Xe</td>
<td>-95</td>
<td>4.3 x 10^6</td>
<td>-0.1</td>
</tr>
<tr>
<td>Au</td>
<td>-70</td>
<td>3.6 x 10^6</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

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The relative importance of the ion species and ion energy in inducing SEGR is still uncertain, limiting our ability to identify if or when a heavier ion species with a lower LET will be more likely to induce SEGR than a lighter species with a higher LET (Fig. 7). Modeling and careful experimental validation will help to define these boundaries, enabling improved SEGR rate estimations.

VI. CONCLUSION

A simulation-based method has been demonstrated to examine whether typical derating of high-energy heavy-ion accelerator test data bounds the risk for SEGR for the much higher-energy space environment. To this end, the SEGR susceptibility of two very different VDMOS devices (a 500V commercial p-type and a 200V radiation hardened n-type) was modeled. This work suggests that a typical derating factor of 0.75 applied to a SEE response curve developed with high-energy test data provides reasonable on-orbit hardness assurance, although in the higher-voltage pVDMOS, it did not bound the risk of failure.

The simulation methodology demonstrated here may only require low-energy accelerator test data for model calibration. These models may be used to generate multiple SEE response curves to examine the sensitivity of the device to changes in ion species and energy, enhancing assurance of on-orbit success without the expense of testing at ultra-high energy facilities. Along with an analysis of the relevant GCR environment, these simulation-based studies may offer a trade-space with other mission concerns such as power and cost.

ACKNOWLEDGMENT

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REFERENCES

Fig. 1. Single-event effect response curves for the 200V nVDMOS showing energy dependence at the higher LET. Y-error bars show measurement uncertainty. Br derating factors = 0.75 Vds and 0.6 Vgs.

Fig. 2. Successful calibration of 200V model to 4 MeV/u vendor data.

Fig. 3. 200V nVDMOS model predicts 12 MeV/u TAMU data.

Fig. 4. Simulated SEGR threshold Vds as a function of Vgs for Au ions versus SOAs defined from derating the 200V nVDMOS test data.

Fig. 5. Single-event effect response curves for the 500V pVDMOS showing good agreement between simulated and test data.
Fig. 6. Simulated SEGR threshold $V_{ds}$ as a function of $V_{gs}$ for simulated Au ion strikes versus 0.75 derating factor applied to test and simulated SEE response curves for the 500V pVDMOS.

Fig. 7A. Heavy-ion flux as a function of ion species and energy.

Fig. 7B. Zoom-in of spectrum showing the hardness assurance provided by the SEE response curve for Br; the region of fluxes of ions with LET $> 40$ MeV-cm$^2$/mg is the uncovered area indicated.

Fig. 7C. Zoom-in of spectrum showing the hardness assurance provided by the SEE response curve defined by Ag; the region of fluxes of ions with LET $> 40$ MeV-cm$^2$/mg is the uncovered area indicated and the low-Z, low-E partially covered area.
Fig. 7D. Zoom-in of spectrum showing the hardness assurance provided by the SEE response curve defined by Au; the region of fluxes of ions with LET > 40 MeV·cm²/mg is the uncovered and partially covered area indicated.

Fig. 8. Cartoon cross-section of a vertical power MOSFET.

Fig. 9. Cartoon showing device response to an ion strike to the drain neck region.