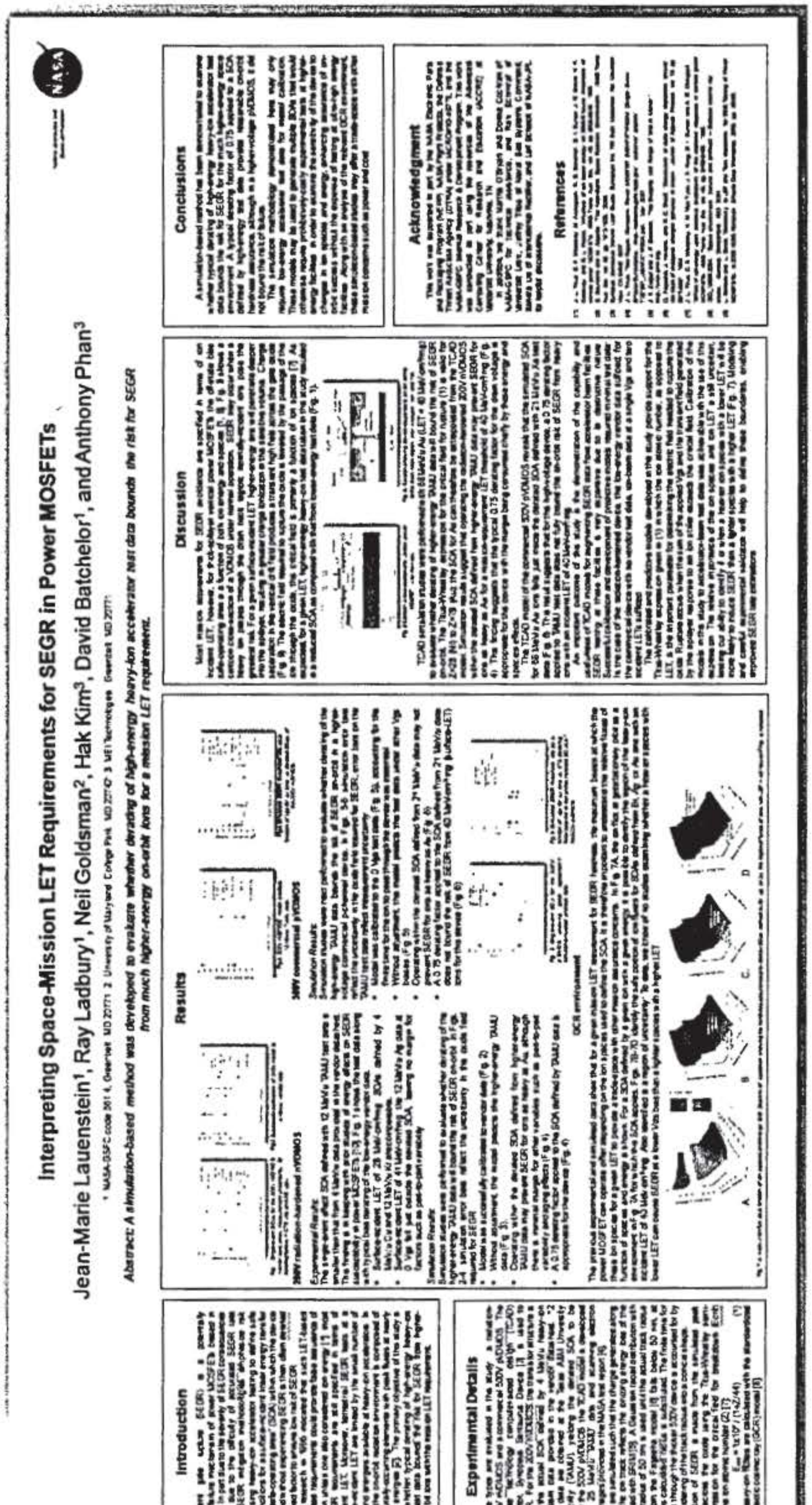
# Interpreting Space-Mission LET Requirements for SEGR in Power MOSFETs

Jean-Marie Lauenstein[1], Ray Ladbury[1], Neil Goldsman[2], Hak Kim[3], David Batchelor[1], and Anthony Phan[3]

1. NASA-GSFC code 561.4, Greenbelt, MD 20771; 2. University of Maryland, College Park, MD 20742; 3. MEI Technologies, Greenbelt, MD 20771.



# Introduction

Single-event gate rupture (SEGR) is a potentially catastrophic failure mechanism of power MOSFETs biased in the off-state. In part due to the severity of SEGR consequences and in part due to the difficulty of accurated SEGR rate estimation, SEGR mitigation methodologies emphasize risk avoidance, using heavy-ion accelerator testing 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 is then often derated by a prescribed factor to ensure low risk of SEGR.

Although research in 1996 indicated that such LET-based SEGR hardness requirements could provide false assurance of safe operation unless one also considered ion energy [1], most mission SEGR requirements 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 [2]. 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.

# Experimental Details

Two device types are evaluated in this study: a radiation-hardened 200V nVDMOS and a commercial 500V pVDMOS. The general-purpose technology computer-aided design (TCAD) device simulator, Synopsys Sentaurus Device [3], is used to simulate SEGR. For the 200V nVDMOS, the transistor structure is calibrated to the actual SOA defined by 4 MeV/u heavy-ion accelerator beam data provided in the vendor datasheet. 12 MeV/u beam data are obtained at the Texas A&M University Cyclotron Facility (TAMU), yielding the derated SOA to be evaluated. For the 500V pVDMOS, the TCAD model is developed from existing 25 MeV/u TAMU data and scanning electron microscope images provided in the NASA test report [4].

Ion strikes are simulated such that the charge generated along the length of the ion track reflects the ionizing energy loss of the ion as calculated with SRIM [5]. A Gaussian radial distribution with characteristic radius of 50 nm is used until the actual track radius determined from the Fageeha model [6] falls below 50 nm, at which point this calculated radius is substituted. The finite time for the ion to pass through the thicker 500V device is accounted for by appropriate widening of the track radius into a conical shape.

Determination of SEGR is 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) [7]:

$$E_{crit} = 1x10^7 / (1+Z/44) \quad (1)$$

On-orbit heavy-ion fluxes are calculated with the standardized ISO15390 galactic cosmic ray (GCR) model [8].

## Results

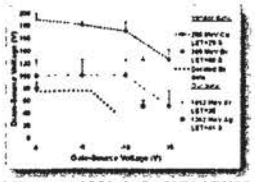


Fig 1 Single-event SOAs for the 200V nVDMOS Y-error bars show measurement uncertainty Br derating factors = 0.75 Vds and 0.6 Vgs..

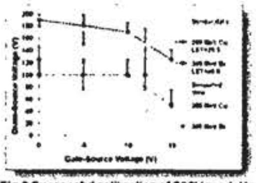


Fig.2 Successful calibration of 200V model to 4 MeV/u vendor data.

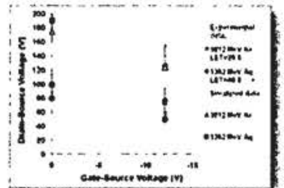


Fig.3. 200V nVDMOS model predicts 12 MeV/u TAMU data.

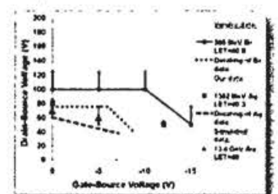


Fig 4 Simulated SEGR threshold Vds as a function of Vgs for Au ions vs. derated SOAs of the 200V nVDMOS

### 200V radiation-hardened nVDMOS

*Experimental Results:*

The single-event effect SOA defined with 12 MeV/u TAMU test data is smaller than that from 4 MeV/u data provided in the vendor datasheet. This finding is in keeping with prior studies of energy effects on SEGR susceptibility in power MOSFETs [10]. Fig. 1 shows the test data along with typical bias derating of the low-energy vendor data.

- Surface-incident LET of 28 MeV-cm$^2$/mg: SOAs defined by 4 MeV/u Cu and 12 MeV/u Kr are comparable.
- Surface-incident LET of 41 MeV-cm$^2$/mg: the 12 MeV/u Ag data at 0 Vgs fall just outside the derated SOA, leaving no margin for factors such as part-to-part variability.

*Simulation Results:*

Simulation studies were performed to evaluate whether derating of the higher-energy TAMU data will bound the risk of SEGR on-orbit. In Figs. 2-4, simulation error bars reflect the uncertainty in the oxide field required for SEGR.

- Model was successfully calibrated to vendor data (Fig. 2).
- Without adjustment, the model predicts the higher-energy TAMU data (Fig. 3).
- Operating within the derated SOA defined from higher-energy TAMU data may 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 (Fig. 4).
- A 0.75 derating factor applied to the SOA defined by TAMU data is appropriate for this device (Fig. 4).

### 500V commercial pVDMOS

*Simulation Results:*

Simulation studies were next performed to evaluate whether derating of the high-energy TAMU data bounds the risk of SEGR on-orbit in a higher-voltage commercial p-channel device. In Figs. 5-6, simulation error bars reflect the uncertainty in the oxide field required for SEGR; error bars on the TAMU test data reflect measurement uncertainty.

- Model was calibrated to the 0 Vgs test data (Fig. 5); accounting for the finite time for the ion to pass through the device was essential.
- Without adjustment, the model predicts the test data under other Vgs biases (Fig. 5).
- Operating within the derated SOA defined from 21 MeV/u data may not prevent SEGR for ions as heavy as Au (Fig. 6).
- A 0.75 derating factor applied to the SOA defined from 21 MeV/u data does not bound the risk of SEGR from 40 MeV-cm$^2$/mg (surface-LET) ions for this device (Fig. 6).

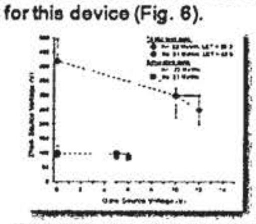


Fig 5 Single-event SOA for the 500V pVDMOS showing good agreement between simulated and test data.

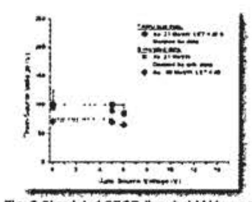
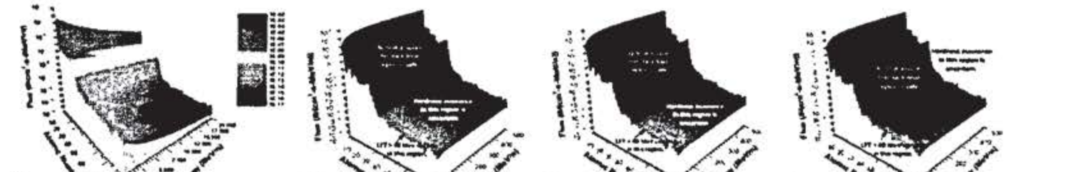


Fig 6 Simulated SEGR threshold Vds as a function of Vgs for Au ions vs. 0.75 derating factor applied to test and simulated SOAs of the 500V pVDMOS.

### GCR environment

The previous experimental and simulated data show that for a given mission LET requirement for SEGR hardness, the maximum biases at which the power MOSFET can operate differ depending on the ion species used to define the SOA. It is therefore important to understand the relative fluxes of these ion species for a given LET to provide a trade-space with other mission assurance concerns. In Fig. 7A, the ion flux at geostationary orbit as a function of species and energy is shown. For a SOA defined by a given ion with a given energy, it is possible to identify the region of the heavy-ion environment in Fig. 7A for which this SOA applies. Figs. 7B-7D identify the safe portion of ion fluxes for SOAs defined from Br, Ag, or Au ions with an incident LET of 40 MeV-cm$^2$/mg. Also identified is a region of uncertainty: To date, we know of no studies examining whether a heavier species with lower LET can cause SEGR at a lower Vds bias than a lighter species with a higher LET.



A. B. C. D.

Fig 7 A. Heavy-ion flux as a function of ion species and energy B-D: Zoom-in of spectrum showing the hardness assurance provided by SOAs defined by Br, Ag, or Au, the region of fluxes of ions with LET > 40 MeV-cm$^2$/mg is indicated

# Discussion

Most mission requirements for SEGR avoidance are specified in terms of ion incident LET; however, for thick-epilayer vertical power MOSFETs the off-state bias safe-operating area is a function of both ion energy and species [1, 9]. Fig. 8 shows a cartoon cross-section of a VDMOS under normal operation. SEGR may occur when a heavy ion passes through the drain neck region; normally-incident ions pose the greatest risk. For a given surface-incident LET, higher-energy ions will penetrate deeper into the epilayer, resulting in greater charge ionization in this sensitive volume. Charge separation in the vertical drift field produces a transient high field across the gate oxide (Fig. 9). The electric field required to rupture the oxide is lowered by the passage of the ion through the oxide; this critical field is primarily a function of ion species [7]. As expected, for a given LET, higher-energy heavy-ion test data taken in this study resulted in a reduced SOA as compared with that from lower-energy test data (Fig. 1).

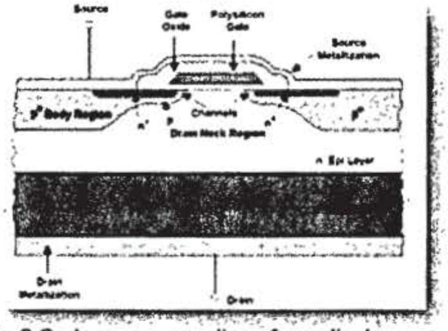


Fig. 8 Cartoon cross-section of a vertical power MOSFET. *After: IR AN1064.*

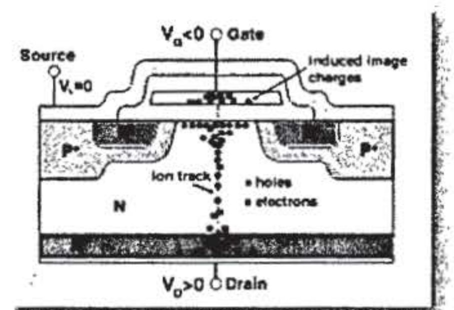



Fig. 9. Cartoon showing device response to an ion strike to the drain neck region. *After: Allenspach, 1994 IEEE TNS*

TCAD simulation studies were performed with 68 MeV/u Au (LET = 40 MeV-cm$^2$/mg)

MOSFET. *After IR AN1064.* to the drain neck region. *After Allenspach, 1994 IEEE TNS*

TCAD simulation studies were performed with 68 MeV/u Au (LET = 40 MeV-cm$^2$/mg) to evaluate whether derating of higher-energy TAMU data will bound the risk of SEGR on-orbit. The Titus-Wheatley expression for the critical field for rupture (1) is valid for Z=28 (Ni) to Z=79 (Au); the SOA for Au can therefore be extrapolated from the TCAD model. Simulation results suggest that operating the radiation-hardened 200V nVDMOS within the derated SOA defined from higher-energy TAMU data may prevent SEGR for ions as heavy as Au for a mission-requirement LET threshold of 40 MeV-cm$^2$/mg (Fig. 4). This finding suggests that the typical 0.75 derating factor for the drain voltage is appropriate for this device, with the margin being consumed chiefly by these energy and species effects.

The TCAD model of the commercial 500V pVDMOS reveals that the simulated SOA for 68 MeV/u Au ions falls just inside the derated SOA defined with 21 MeV/u Xe test data (Fig. 6). This result suggests that for this high-voltage device, a 0.75 derating factor applied to TAMU test data does not fully bound the on-orbit risk of SEGR from heavy ions with an incident LET of 40 MeV-cm$^2$/mg.

An important outcome of this study is the demonstration of the capability and usefulness of TCAD models for augmenting SEGR data from accelerator beam facilities. SEGR testing at these facilities is very expensive due to its destructive nature. Successful calibration and development of predictive models required minimal test data: In the case of the radiation-hardened device, the low-energy vendor data sufficed; for the commercial device with no vendor test data, ion-beam data at a single Vgs and two incident LETs sufficed.

The calibrated and predictive models developed in this study provide support for the Titus-Wheatley expression given in (1) in which the ion atomic number, as opposed to LET, is the important parameter for determining the electric field needed to rupture the oxide. Rupture occurs when the sum of the applied Vgs and the transient field generated by the epilayer response to an ion strike exceeds this critical field. Calibration of the models in this study to accelerator-beam test data was achievable with the use of this expression. The relative importance of the ion species and ion LET 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.

# Conclusions

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. A typical derating factor of 0.75 applied to a SOA defined by high-energy test data provides reasonable on-orbit hardness assurance, although in a 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 SOAs that would otherwise require prohibitively-costly experimental tests at higher-energy facilities, in order 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.

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