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Review—Opportunities in Single Event Effects in Radiation-Exposed SiC and GaN Power Electronics

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Radiation effects have a critical impact on the reliability of SiC and GaN power electronics and must be understood for space and avionics applications involving exposure to various types of ionizing and non-ionizing radiation. While these semiconductors have shown excellent radiation hardness to total ionizing dose and displacement damage effects, SiC and GaN power devices are susceptible to degradation from single event effects (SEE) resulting from the high-energy, heavy-ion space radiation environment (galactic cosmic rays) that cannot be shielded. This degradation occurs at <50% of the rated operating voltage, requiring operation of SiC MOSFETs and rectifiers at de-rated voltages. SEE caused by terrestrial cosmic radiation (neutrons) have also been identified by industry as a limiting factor for the use of SiC-based electronics in aircraft. In this paper we review prospects and opportunities for a comprehensive and systematic assessment of these materials to understand the origin and possible mitigation of these effects.
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The two commercialized wide bandgap semiconductors SiC and GaN are of interest for more energy efficient power electronics that can withstand higher operating temperatures, have increased durability and a smaller form factor than Si devices.[1] These have applications in improved electrical grids, electric and hybrid-electric transportation, greater integration of renewable power sources, and higher efficiency electric motors for use in heavy industries and consumer appliances. These power electronics enable significant efficiency gains across the economy, reducing energy costs and electricity consumption.[1]

They are also applicable to space and commercial avionics applications where they will be subject to significant radiation exposure,[2–8] even missions to Venus based on their capability to operate at very high temperatures.[9] In these applications, their radiation tolerance is the key enabler.[10–19] How to quantify radiation hardened microelectronics for nuclear, defense and space applications is an increasingly important topic.[20–62] A complex and time-dependent spectrum of galactic cosmic and solar particle radiation continually bombards the Earth’s upper atmosphere.[3,6–8] The components of this cosmic radiation spectrum interact with the atmosphere, producing secondary radiation. The amount of radiation exposure caused by this primary and secondary radiation increases with increasing altitude.[8] Ion fluxes for the International Space Station are ~30 ions cm^{-2} per day with a linear energy transfer (LET) value greater than 1 $MeVcm^2\ mg^{-1}$.[7,8] At aircraft altitudes, (commercial—10 km, and military supersonic, 17–20 km) nearly all ionizing radiation exposure is from secondaries.[7] Primary incident ions break up into secondaries through nuclear interactions. The intensity of secondary particle flux reaches a maximum at about 65,000 ft (20 km). For high altitude aircraft, the dose equivalent rate of protons at this Pfotzer Maximum is 400x that at sea level and 6x higher at the poles compared to the equator.[7,8] The effective dose for a single flight from San Francisco to Paris is ~85 μSv, which compares to an annual exposure of 3 mSv for civil aircrews.[7] It is worse for space craft outside the atmosphere, where spacecraft electronics have a long history of power resets, safing, and system failures due to long duration exposures, unpredictable solar proton activity and ambient galactic cosmic ray environment.[3,5]

The three common methods to mitigate radiation effects in avionics are use of radiation hardened devices, triple module redundancy or use of error detection/correction algorithms. The first two require shielding or add complexity while the latter cannot handle a swarm of errors. Single-event upset hardening approaches include RC delay hardening and design approaches based on either internal redundancy or blocking current transients, such as stacked transistors.

Basics of Radiation Effects

The main sources of energetic particles of concern in space and avionics application are: protons and electrons trapped in the Van Allen belts, heavy ions trapped in the Earth’s magnetosphere, cosmic ray protons and heavy ions of multiple elements, and protons and heavy ions from solar flares.[8] The four main major radiation effects are total ionizing dose (TID), displacement damage (DD) single event effects (SEE) and prompt dose. In space, the major source of TID is electrons and protons, while on earth, it’s mostly due to X-rays and gamma rays. TID is the result of an accumulated ionizing dose which causes charging of dielectrics in a device, eventually leading to failure. Ionizing radiation (such as gammas) usually does not give rise to additional traps in the bulk. Electrons and/or holes generated by the ionizing dose radiation do get trapped in existing sites in a dielectric. In the case of SiO_2 grown on Si, essentially only holes do get trapped within the bulk. These can later give rise to interface states, increased leakage and soft breakdown.[8] Mitigation approaches for TID include either using circuits sufficiently radiation-hard they can withstand the dose during the mission or to use shielding, which adds cost and weight to the system.

Displacement damage is caused by ions colliding with the semiconductor lattice. The defects created act as carrier traps and also degrade carrier mobility. SEE are caused by high-energy protons or heavy ions in space, while on earth, the main cause is neutrons. A single event effect occurs when a single heavy ion or high-energy proton impacts a device. This ion will create a trail of hole and electron pairs which can be swept into the electric field of the device. A heavy ion strike can cause different kinds of effects, both non-destructive and destructive.[8] The destructive single event effects are single event burnout (SEB), single event gate rupture (SEGR), and single event dielectric rupture (SEGR). SEB and SEGR

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are different mechanisms, but they can be hard to distinguish.[8] SEB generally refers to a localized nature of the high current flow, resulting in damage from excessive Joule heating. During an SEB event, current does not need exceed the device rating. In other words, single-ion-induced strike causes a localized high-current state, which may result in catastrophic device failure. SEGR in power MOSFETs is caused by electrons or holes piling up under the gate, momentarily resulting in high field, exceeding the breakdown field of the partially damaged dielectric. The gate oxide gets destroyed from one or more than one ion strike. The susceptibility to SEB and SEGR is both voltage- and current-dependent. For commercial products that exhibit SEB and SEGR, it can become necessary to derate these products for space missions.[39] Finally, there are single-event functional interrupt (SEFI), in which a soft error causes a device or circuit to reset or lock-up, but does not require power cycling to restore operability, unlike single-event latch-up (SEL), or result in permanent damage as in single event burnout (SEB).

SEE are one-time events caused by a high-energy particle striking a device and resulting in an event, such as a current transient, an upset, a latch-up, or damage. A key parameter is the Linear Energy Transfer (LET), which is the amount of energy transferred per unit length per density of the material as the ion travels through a material, expressed as MeV/(mg cm^{-2}) or linear energy divided by density, the ion stopping power for a given target. The cross section is the number of errors produced in the device under test divided by the fluence, in units of cm^2. The cross section gives a probability of a single event occurring. To simulate these effects, testing has traditionally been done with an accelerator. Many of the high-energy heavy ions and protons encountered in space typically cannot be shielded, so mitigation involves adding redundancy or reset circuitry. Prompt dose is also referred to as dose rate upset or dose rate latch-up and is caused by a flash of high energy photons from a nuclear explosion. This results in large photocurrents developing inside the devices or circuits. The dose rate here is many orders of magnitude higher than used for TID testing. The photocurrents can cause effects similar to single event effects, but multiple effects can occur at once. Some bipolar technologies also exhibit enhanced low dose rate sensitivity (ELDRS), resulting from buildup of hydrogen ions at the Si/SiO_2 interface.

The most common unit for expressing radiation dose in electronics is the Rad or Radiation Absorbed Dose. A rad is the dose causing 100 ergs of energy to be absorbed in one gram of matter. The medical community use Gray as their radiation unit, which is an international standard unit. One Gray equals 100 rad. Currently, small satellite applications require a Total Ionizing Dose (TID) resilience of 30 krad (Si) and Single Event Latch-up (SEL) hardened up to 80 MeV-cm^2 mg^{-1} linear energy transfer.

The standard radiation test is an accelerated test done at a high dose rate. Originally all non-destructive single event effect was termed an SEU, but that definition is now narrowed to a digital bit flipping from either a one to a zero, or a zero to a one. Almost all devices will exhibit SEUs when tested with heavy ions. Heavy ion testing is done at a cyclotron. There are only a few of these facilities in the US or in Europe, and beam time is expensive- $1,000–4,000 per hour.

In DD testing, neutrons can be used instead of protons to separate out ionizing dose effects from the displacement damage. In some testing, a device will go through DD, followed by total ionizing dose testing to see the cumulative effect of displacement damage and TID.[8]

Regardless of high-tolerance to external radiation, one of the reliability issues for wide bandgap semiconductor-based devices is in the impact of radiation on material's properties and device characteristics. While SiC and GaN power devices are commercialized for use in automotive, wireless, and industrial power markets, their adoption into space and avionic applications is hindered by their susceptibility to permanent degradation and catastrophic failure from heavy-ion exposure. Recent radiation testing of 600-V and higher GaN transistors has shown failure susceptibility at $\sim$ 50% of the rated voltage.[45,46] SEE caused by terrestrial cosmic radiation (neutrons) have also been identified by industry as a limiting factor for the use of SiC-based electronics in aircraft.[37–42] Si-based technologies such as Fully-Depleted Silicon-on-Insulator and Fin Field-Effect Transistors (FinFETs) have inherent hardness to single-event effects because of their reduced sensitive area. These can survive space radiation environments with total ionizing dose (TID) $>$100 krads (Si), single event upsets (SEU) $< 10^{-10}$ errors/bit-day, and immunity to single event latch-up (SEL) at linear energy transfer (LET) levels $>$ 75 MeV cm^2 mg^{-1}.

Transient Ionization Effects

The energy of ions incident on a device spans a large range. For example, electrons trapped in the Van Allen belts have energies up to tens of MeV, while trapped protons and heavier ions can have energies up to hundreds of MeV. The flux of protons from solar flares can also have energies up to hundreds of MeV, while heavy ions from this source can have energies in the GeV range.[3,8,10] Finally, galactic cosmic rays can have energies in the TeV range. There is a hierarchy of phenomena that can occur when any of these types of radiation pass through a device and often the nomenclature can be confusing as different device outcomes can be referred to by the same name. In general, Single-Event Upsets (SEU) is used to describe transient state changes of memory or register bits caused by a single ion interaction. As described earlier, Single-Event Latch up (SEL) occurs when passage of the ion causes a latched state that is held until the power is cycled. If the state causes high current flow, permanent damage can occur. In a Single-Event Transient (SET), the charge collected from an ionization event results in a spurious signal propagating through the circuit.[3]

Heavy-ion irradiation of SiC power devices in the biased off state results in either catastrophic failure, or at lower voltage, a phenomenon labelled single-event leakage current (SELC) in which the ion causes thermal damage resulting in a permanent increase in the device leakage current. SELC differs from displacement damage in that it requires ionized charge in a high electric field. It is expected that similar effects occur in GaN devices, but there may be differences due to the generally higher defect densities in the material and the absence of gate oxides due to the more widespread use of metal gates in GaN technology. One of the main SEE radiation requirements are derived in part by the environment specified as a function of linear energy transfer (LET) in silicon.

Device Penetration of Heavy Ions and Linear Energy Transfer (LET)

As mentioned earlier, the inelastic LET characterizes the energy deposition of charged particles and is based on the average energy loss per unit path length (stopping power). The density of the semiconductor is used to normalize LET to the target material.[8]

$$\mathrm{LET} = \left(\frac{1}{\rho}\right)(dE/dX)\,\text{in units of MeV.cm}^2\text{.mg.}$$

The SEU Cross sections (σ_{seu}) characterize how many upsets will occur based on ionizing particle exposure and is typically calculated at several LET values to give an idea of the response to the type of particle spectrum encountered in or above the atmosphere. It is also important to differentiate between the flux of ions (ions. cm^{-2}.sec^{-1}) and fluence, which is the flux integrated over time (in units of ions.cm^{-2}).

Radiation damage occurs through electronic (ionizing and charge transfer) effects and nuclear displacement damage. The LET to the electronic structure from incident particles (also known as electronic stopping power), as well as from photons (X-rays and lasers), results in creation of energetic electrons (i.e., ionization and excitation) that initially dissipate their energy in a cascade of electron-electron energy transfers.[63–73] This superheating produces electron-hole (e-h) pairs on the time scale of femtoseconds. Simulations of the passage of energetic heavy ions have indicated that most of this energy is then transferred to the lattice by electron-phonon (e-ph) coupling.[63–73] The transfer of this large amount of energy creates a local thermal spike on the time scale of a few hundreds of femtoseconds. This in turn produces localized electronic excitations capable of rupturing the covalent/or ionic bonds present in the semiconductor and cause defect migration. This is a drawback of current TCAD modeling approaches, in which, SEEs are simulated using a Gaussian pulse with a time sigma of approximately one picosecond, which does not accurately capture the essential physics. Similarly, the effect of the extreme temperature rise possible under some fast heavy ion conditions is not treated in TCAD approaches.

It is important to realize the potential for significant local changes in lattice structure along the track of the incident ion, particularly for heavy ions with atomic numbers higher than those of the lattice constituents In the past, it has often been assumed by device technologists that SEE involves only a localized spike of ionization along the ion track which can affect the local electric field profile and also lead to impact ionization as the charge is separated by the electric field present. The simulation of this process and recent experimental observations of extended defect creation indicate that even while displacement damage is generally not considered at the high energies typical of SEEs, there can indeed be substantial local changes in lattice structure, with permanent device implications.[63] The short time frame ($<$100 psec) transient ionization-induced processes associated with high LET particles and intense pulses of photons into confined dimensions ($<$10 nm radius in case of charged particles) mean very high local temperature spikes occur, above the melting temperature of the semiconductor in some cases.[63–73]

It is of course, challenging to experimentally observe the lattice damage, since the ion fluence is small and finding a single ion track is extremely difficult with transmission electron microscopy unless amorphous tracks are formed, which is generally not the case for SiC and GaN. From a modelling viewpoint, the ionization-induced thermal spike is difficult to describe with simple dynamics or thermally activated processes. Even the strike of a single ion causes the creation of free charge carriers and atomic defects through ionization in the device that can temporarily or permanently disrupt its functionality, as in single event upsets and single event burnout, respectively.[74] At high ion energies and intense laser or gamma pulses, the energy transferred to the atomic structure via e-ph coupling can cause an intense transient thermal spike that can cause a shock wave, local heating or melting, followed by a fast quench and related defect formation.[63] In the case of single ions, the thermal spike has a cylindrical geometry, while for an X-ray burst or lasers, the thermal spike has a planar geometry relative to the surface.[57]

SEE Testing

As mentioned earlier, it is expensive and time-consuming to simulate SEE with ion accelerators and this is sufficiently a bottleneck that the National Academies recently produced a study on the status of accelerator-based testing in the US.[3] In addition, most of these facilities offer small fluences but not true single event capability. There is no facility in the USA that can produce single ions focused on a specific spot or device. Most testing at high ion energies are done using cyclotrons or other large machines, such as at Brookhaven, Texas A&M and Lawrence Livermore. These experiments are done at a constant energy and low flux, so many single events are registered, but it can be a challenge to find defective regions for TEM characterization, since there may be only $\sim 10^{11}$ ion hits per cm^2. In-situ TEM can be performed on devices irradiated with high LET ions (10's of MeV.cm^{-2}.mg) to look for single ion hits. Post-irradiation TEM on non-amorphous tracks reveal radial chemistry changes and strain fields, ejected interstitials and punched out dislocations.

To produce a single ion hit on device, both GSI Helmholtz Centre for Heavy Ion Research in Darmstadt in Germany and the Heavy Ion Research Facility in Lanzhou (HIRFL), also called Lanzhou Heavy Ion Accelerator, in China have microprobe capabilities that can produce a single ion impact at a resolution of 500 nm-the facility at GSI is used by the European Space Agency to test devices, and they can control to within 500 nm where a single ion will hit the device, which is really a single ion test.

There has been significant effort to use pulsed lasers and focused X-rays to generate SEEs in a manner akin to heavy ions, while offering refined spatial and temporal control of charge generation within devices.[54–58] Charge generation profiles for the three testing methods vary in the axial and radial dimensions. Heavy ions typically have linear charge generation profiles along the axial direction in the device. By contrast, typical focused femtosecond pulsed-laser systems use optics that produce a charge generation profile described by single photon absorption (SPA) or Gaussian two-photon absorption (TPA).[54–58] If laser photon energy is above material bandgap then it is a SPA process. If laser photon energy is below bandgap then it is TPA process.

As demonstrated recently, there are differences in the response to single ions compared to a pulsed laser, and these warrant more investigation.[57] The e-h pair density produced by 10 to 20 MeV ions is similar to that in pulsed laser studies. The difference is the radial spatial distribution, where the e-h pairs are confined to a column a few nm to several 10's of nm in radius, while the pulsed lasers produce e-h in a 3D—XYZ. The latter has a Gaussian shape in the lateral direction and either Gaussian or asymmetric quasi Bessel in the axial direction. Laser beam FWHM at the focal point is less than micron. Charge distribution profile in lateral direction is several microns. Certainly, alternative SEE testing methods show promise for basic research and ad hoc correlations to heavy ion testing and an understanding of the dissipation of ionization and ballistic energy in semiconductors as a result of SEEs from cosmic/solar radiation or an intense X-ray burst.

It is typical in SEE testing to irradiate the device under test with different ions (e.g., H, C through Ni) to produce different linear energy transfer (LET) heavy ions at energies up to 25 MeV (LET $\sim$ 30 MeV/(mg cm^{-2}) to simulate the response to cosmic/solar radiation. In addition, pulsed lasers, ^{60}Co gamma sources, neutrons and electron beams can be used to separate the combined effects of ionization and displacement damage processes. A major need is more emphasis on in situ ion and laser irradiation while simultaneously imaging defect production and evolution. Irradiations at higher energies ($>$100 MeV) and LET can also be carried out at special high energy facilities, such as the NASA Space Radiation Laboratory or the Cyclotron Institute at Texas A&M University (TAMU).

For SiC vertical power devices, NASA requirements call for no heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident linear energy transfer (LET) of 40 MeV-cm^2 mg^{-1} and sufficient energy to maintain a rising LET level throughout the epitaxial layer.[74] For all other devices, there should be no heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration with ions having a silicon-equivalent surface-incident LET of 75 MeV-cm^2 mg^{-1} and sufficient energy to fully penetrate the active volume prior to the ions reaching their maximum LET value.[74] These parameters concern the non-catastrophic heavy-ion induced permanent leakage current degradation susceptibility of SiC MOSFETs and rectifiers. The degradation referred to is due to ionizing energy loss of heavy ions as opposed to displacement damage in the crystal lattice. The need is to exceed the performance of existing heavy ion SEE-tolerant Si power devices, which include Schottky rectifiers capable of 600 V, 30 A, and 27-ns recovery time, and MOSFETs capable of 650 V, 8 A, with on-state resistance of 450 mOhm.[74] With SiC-based Schottky diodes, catastrophic single-event burnout (SEB) and other single-event effects (SEE) have been

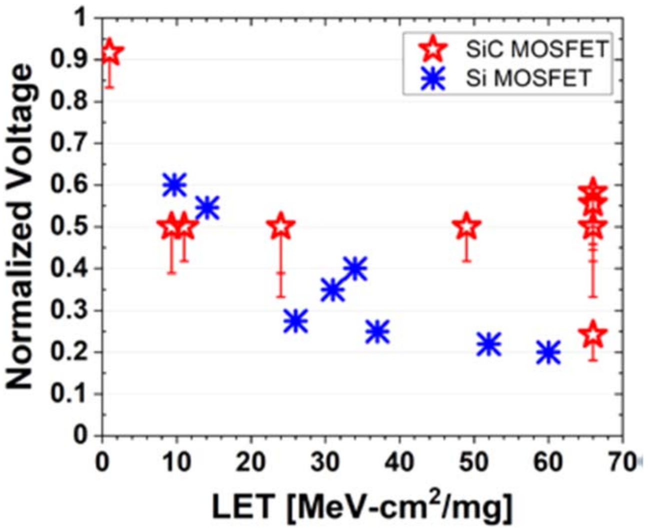

Figure 1. Normalized drain-source voltage at which SEB occurs in SiC and Si power MOSFETs as a function of LET (from Lauenstein[39]), reproduced with permission, copyright IEEE.

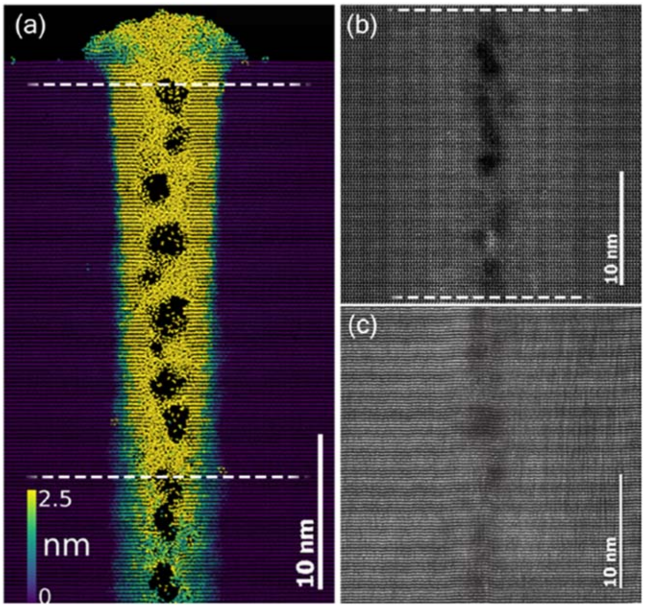

Figure 2. Cross-sectional images of the final state of a track formed by a 185 MeV Au ion near the GaN surface. (a) represents the simulated track with the color scale representing the magnitude of displacement of the atoms from their initial positions. (b) is the simulated transmission electron microscopy–high-angle annular dark-field image corresponding to the area delimited by the dashed lines in (a).(c) is the corresponding experimental cross-sectional image of a track near the surface of GaN irradiated with a fluence of 1 × 10^{11} cm^{-2}. (reprinted with permission from Miguel C. Sequeira, Jean-Gabriel Mattei, Henrique Vazquez, Flyura Djurabekova, Kai Nordlund, Isabelle Monnet, Pablo Mota-Santiago, Patrick Kluth, Clara Grygiel, Shuo Zhang, Eduardo Alves and Katharina Lorenz,[63] open access article licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format.

observed at $\sim$40% of the rated operating voltage, as well as an unacceptable degradation in leakage current at $\sim$20% of the rated operating voltage.[39,40] Recent radiation testing of 600-V and higher GaN transistors has shown failure susceptibility at about 50% or less of the rated voltage.[45–47]

Figure 1 shows the SEB threshold during irradiation in 0.9–-3.3 kV SiC and 200 V Si power MOSFETs as a function of ion LET. MOSFETs are more susceptible to additional heavy-ion damage effects relative to rectifiers,[39,40] mainly due to damage to the gate oxide. The gate oxide suffers increased gate oxide leakage current. The SiC MOSFETs displayed this damage to the gate oxide at low values of rated breakdown voltage, from ions with LET > $\sim$10 MeV·cm^2 mg^{-1}. In addition, vulnerability to immediate catastrophic failure was present at an LET of 1 MeV·cm^2 mg^{-1}.[39,40] The threshold voltage for immediate catastrophic SEB saturates with LET at $\sim$50% of the rated voltage. The mechanism is strongly electric-field dependent. There was no latent damage to the gate from low LET/light ions, while the onset is independent of MOSFET voltage rating at higher LETs. By contrast, in SiC Schottky diodes, electric field may not be a primary factor. As single ion flux increases, there is a degradation in reverse leakage current until there is a sudden catastrophic failure and the device has undergone single event burnout, i.e. no longer able to perform as a rectifier. There is no difference observed between Schottky and PIN diodes.[39,40]

There have not yet been definitive studies to determine if these devices will be more susceptible if an incident ion strikes near the highest field region, e.g., at the edge of the contact on a rectifier. It may also be the case that a highly strained region might be more susceptible to a defect being created there if some threshold energy is deposited and may even have a coincidence of the two effects if an edge termination method is employed that creates strain at the edge of the contact where the field is highest. It is possible that the trajectory of the ion strike and the magnitude of the field dominate the susceptibility of SiC and GaN devices to SEE. It has been shown that ion trajectory has a major influence on single event upsets in devices, since the angle of incidence affects the effective LET.[43]

High Al-content AlGaN/GaN HEMTs.—A group from Sandia reported heavy ion and proton data on high Al content AlGaN High Electron Mobility Transistors (HEMTs) showing single event burnout (SEB), total ionizing dose, and displacement damage responses.[44] Devices with $Al_{0.7}Ga_{0.3}N$ channels showed burnout voltages that decreased rapidly with increasing LET, failing at 25% of nominal breakdown voltage for ions with LET of 34 MeV.cm^2 mg^{-1}.[44] Devices with $Al_{0.3}Ga_{0.7}N$ channel layers exhibited improved robustness to heavy ions, resulting in burnout voltages that did not decrease up to at least 34 MeV. cm^2 mg^{-1}. The failed devices always showed a shorted location between the high field region between gate and drain where a heavy ion strike occurred.[44]

Conventional Al-content (22%-25% Al) enhancement mode HEMTs have shown strong radiation resistance under gamma, neutron, and proton radiation.[15,17,18,45] Testing showed no measurable degradation after 50 MRad (Si) gamma dose. These devices exhibited strong radiation resistance under heavy ion testing up to 85 MeVcm^2 mg^{-1} and total fluence of 10^7 ions·cm^{-2} with a 15 MeV amu^{-1} Au beam, and the HEMTs biased at 100 V.[45] Use of a 2 photon absorption laser test system to simulate the ionizing effects of heavy ions in small area ($\sim$20 um diameter) demonstrated the same failure mode observed in SEE.[45] There is a need for more SEE testing on GaN HEMTs since they have no gate oxide and hence TID effects are minimal. In addition, since GaN is a strongly bonded material, and HEMTs are majority carrier device with strong polarization fields, they are relatively insensitive to defects, so displacement damage is also not a major issue. The effect of ion interaction in or near the gate for SEE is the larger risk since stress from charge collection or ion damage to the gate directly leads to failure from damaged HEMT gates.

Destructive SEEs in GaN HEMTs[61,62,67] have been reported due to charge collection and damage from heavy ions and destructive SEE in RF devices.[48–53] GaN HEMTs with insulated gates have also been studied for SEE.[48–52] One advantage of the pulsed laser SEE approach in this regard is that it is non-destructive. Of course, at very high pulse energies there would be optically-induced damage to the device, but those energies are much higher than normally used. Studies on GaN Schottky-gate and MIS-gate HEMTs with pulsed X-rays did report device degradation in the case of MIS-gate HEMTs.[54,55] Schottky-gate HEMTs were more robust than insulated gate transistors.[54,55]

Causes of the premature single event burnout in SiC and GaN Power Devices.—A major concern is that in SiC-based Schottky diodes, MOSFETs and JFETs, catastrophic SEB and other SEE are observed at ∼40% of the rated operating voltage, as well as a potentially unacceptable degradation in leakage current at ∼20% of the rated operating voltage.[39–41,74] At high LET values, characteristic of so-called high atomic number and high energy ions (HZE) there is an increase in reverse leakage, which progresses to permanent degradation and finally failure through SEB.[39–41] This occurs under conditions where displacement damage is low relative to the NIEL.[39–41]

Sequeira et al.[63] recently reported that swift heavy ions (185 MeV Au) incident on GaN induce ionization spikes and overlapping ion strikes causes recrystallization of the lattice and minimizes the radiation damage. This self-annealing can recover the damage produced in previous ion impacts, including the amorphous cores of previous ion tracks. The dynamical recovery significantly reduces the damage buildup with fluence, preventing the complete amorphization of the GaN and is a prime reason for its resistance to strongly ionizing radiation.[63]

Figure 2 shows the excellent agreement between molecular dynamics simulations of the ion track employing a two-temperature model that considers electronic stopping and electron-phonon interactions and its experimental observation by TEM.[63] There is some sputtering that occurs near the surface due to pressure relaxation, producing voids within the track and a hillock at the entry point. The shape and distribution of the voids inside the highly damaged track is reproduced by the simulation.[63] The largest void has a lateral dimension of ∼4 nm, with density inside the track of 0.30–0.35 voids nm^{-1}.[63]

This is a clear indication that heavy ions create localized lattice defects through the intense ionization/energy deposition process. These will have the same type of effect on device performance as the more commonly studied displacement damage, consisting of point defects. It has not been generally realized that if such damage occurs, SEE at high LET will always degrade device performance. There is a tendency to regard SEE in charge deposition terms with little actual lattice damage and therefore the effects would be due to impact ionization and mechanisms that short the device. The direct observation of such defective regions caused by heavy ion strikes shows that this type of radiation exposure will be of major concern.

Is this common to all wide bandgap semiconductors? More studies of this type are needed, but some characteristics are already established. For example, it is known that AlN is difficult to amorphize under ion irradiation with threshold displacement energies that are strongly dependent on crystallographic direction.[67–69] The damage saturates at a dose of ∼10 displacements per atom (dpa) under heavy ion irradiation, indicating that self-annealing is also prevalent in this material.[68] Molecular dynamics simulations of SiC has shown significant recombination of primary defects during irradiation and the most configurations for C interstitials are $\langle 100\rangle$ and $\langle 110\rangle$ dumbbells on both Si and C sites, while the most favorable Si interstitial is the tetrahedral interstitial site, surrounded by four C atoms.[70–73] The dominant surviving defects are C interstitials and vacancies.[70–73] Islam et al. found a deficiency of N under the gate of Au irradiated GaN HEMTs, along with metal diffusion from the gate.[53] It must now be established if SiC and AlGaN alloys display the same type of damage along heavy ion tracks as does pure GaN. The available evidence suggests this is the case, since the SiC devices exhibit significant degradation at high LET values and the higher Al content AlGaN/GaN HEMTs were more susceptible to heavy ion damage than the more typical 25% Al alloys.

Room Temperature, Ultrafast in situ Damage Mitigation

Since the high energy ions cannot be shielded and the SiC and GaN devices are susceptible to degradation from these ion strikes, are there any simple annealing steps that might remove some of the induced damage? It would be difficult to implement thermal annealing in practical applications, but there are athermal possibilities.

One possible approach is recombination-enhanced athermal annealing due to carrier injection.[75–78] It has been shown that electron injection in p-GaN and p-ZnO lead to pronounced elongation of the diffusion length.[75–78] The partial recovery of radiation degraded transport properties in GaN, AlGaN and Ga_2O_3 has been demonstrated.[75–78] While minority carrier transport is significantly affected by irradiation, the diffusion length can be fully recovered by purely electrical means (forward bias electron injection) and the effect is long lasting. Such an improvement of minority carrier transport has its signature in photovoltaic detector's quantum efficiency.[75–78]

This is a potentially transformative approach to mitigate radiation damage in wide bandgap semiconductors. The basic science of solid-state electron injection (e-injection) needs more investigation and confirmation that the fundamental mechanism is ultra-fast, athermal and purely electrical in nature (in situ device repair with no costly technology modification). In comparison, existing mitigation approaches exploit shielding, device modification, triple module redundancy and error detection-correction algorithms, which are expensive and complex.

The proposed radiation damage mitigation electron injection (e-injection) into GaN due to forward bias (solid-state e-injection) leads to significant and lasting changes (days) in the material's electronic properties.[75,76] The effect of only 60 seconds processing at room temperature on a GaN-based photovoltaic p-*i*-n detector with 1000 Gy dose of gamma-rays showed substantial recovery by applying a short pulse of forward-bias.[75,76] Deterioration of photodetector's response under gamma-irradiation may lead to faulty hostile rocket detection and consequent interception and, therefore, presents a serious homeland security issue.

The basic physics behind this e-injection process (an electron beam can be used, or forward biasing the actual device) is generation of a non-equilibrium population of electron-hole pairs. These carriers recombine either via the band-to-band transition or through unoccupied (non-ionized) acceptor states. However, if a non-equilibrium electron is trapped by the acceptor level, recombination cannot proceed, leading to increased lifetime of non-equilibrium carriers and, therefore, elongation of diffusion length, L (proportional to the square root of lifetime). Release of the trapped electron with an activation energy ΔE_A restores the original recombination pathway, resulting in a slower rate of lifetime increase at elevated temperatures. The uniqueness is the increase of diffusion length, L, by up to one order of magnitude, thus "healing" the adverse impact of radiation and allowing tunability of device performance control.

Are some regions of devices more susceptible to heavy ion damage?—Under normal conditions, creation of charge in the highest field regions should have the most impact on since the carriers will be accelerated to higher energies and possibly create damage through avalanche or thermal runaway mechanisms. However, this inherently assumes that the device is uniform in other types of fields, such as mechanical and thermal. We consider the GaN HEMT as an example, where the maximum field intensity near the gate, facing the direction of the drain.[79,80] Conventional models consider mechanical or thermal stress, but only those arising from the applied electrical stress, which leaves wide opportunities from materials science and engineering perspectives. For example, the presence of more than half micron thick electrodes and/or rapid thermal annealing process may introduce non-uniformity in mechanical and thermal fields.[81]

Strain localization or interfacial thermal conductance are not new concepts,[82] but we observe that they are not always adequately addressed in electronics reliability. We suggest that highly localized mechanical or thermal hotspots may be present in electronic devices, depending on the device design, materials and interfaces, scale of integration and fabrication processing steps. These structural hotspots can potentially lower the energy required to initiate the breakdown during an ion strike. If the field is below the threshold for avalanche, or if impact ionization is not the main breakdown mechanism, that structural hot spot is not necessarily more likely to be the failure point. However, if the electrical hotspot overlaps with the structural hotspot, that region will be "more vulnerable" to failure considering all other variables constant.

Our conjecture on structural hotspot is challenging to because of the highly localized nature of these regions, making conventional interrogation techniques (such as Raman[83]) unsuitable. Transmission electron microscopy (TEM) offers such measurements, albeit it does not alleviate the problem of selecting the exact hotspot location. Figure 3 shows our preliminary findings supporting the above-mentioned conjecture. Here, we prepared a TEM specimen from a commercially available GaN HEMT (Wolfspeed CGHV1J006D 6-W 18.0-GHz). To preserve the stress state as much as possible, we made only the gate to drain region electron transparent. This is shown in Figs. 3a and 3b. We then performed highly localized probing of residual strain in three distinct spots, two of them adjacent to the AlGaN-GaN interface, but one beneath the gate. The third spot was selected in the bulk of the GaN layer. These three locations are also shown in Fig. 3b. We then performed nano-diffraction technique with [2 1 0] = [1 0 −1 0] zone axis and converted the data to real space lattice spacing. In the (0 0 2) planes, vertical direction in all figures) the measured strains are shown in Figs. 3c–3e. In this direction, the equilibrium lattice spacing is 2.590267 Å.[84] The corresponding stress at points 1 and 2 can be estimated to be 1.12 and—2.34 GPa, assuming Young's modulus of GaN to be 300 GPa. It is important to note that these are built-in stresses and not inverse piezoelectric stress components that will be added during device operation.

According to our conjecture, in the "On" state, location 1 is the most vulnerable one for SEE. This agrees well with the laser-based measurements of Single Event Transients (SETs) of similar device.[55] This is shown in Fig. 3f, where the most sensitive areas are observed to be within 2 microns distance from the gate (facing the drain). We suggest that the source of these conjectured structural hotspots is a number of variables, but mostly fabrication processing. Therefore, randomness in the process will dictate the location and degree of localization of the structure hotspots. This is evident in electroluminescence (EL) mapping shown in Fig. 3g.[85] Here, the EL emission is highly non-uniform, probably because of the randomness of the hotspot (both electrical and mechanical) stress intensity. We therefore suggest that if one is able to locate the highest mechanical stress adjacent to the gate (entire length), one can predict that location to be the most vulnerable spot in the On-state operation. Unfortunately, there are only a few techniques to measure such highly localized stress with high spatial resolution. Therefore, the above-mentioned conjecture can be studied in the reverse direction, where we prepare TEM specimens guided by the EL map. In this case, the highest EL intensity region is predicted to exhibit the strongest structural hotspot. Similar study can be performed with an EBIC map in two dimensions, since the technique has higher spatial resolution compared to EL. Thorough study of our conjecture, in combination with a high spatial resolution non-destructive technique to measure sub-micron residual stress hotspots, can identify the most vulnerable regions in HEMTs. This can potentially change the landscape of microelectronic reliability by moving from post-failure analysis to predictive one.

Radiation Test Standards

There is also a need to revise some of the existing radiation test methods.[86–89] For heavy ion testing, one standard for the circuitry is MIL-STD-750 TM1080. This method provides a framework for standardized testing of heavy ion irradiation of power MOSFETs to establish SEB and SEGR.[87] This is a specific test from a more general standard for testing semiconductors, MIL-STD-750D from

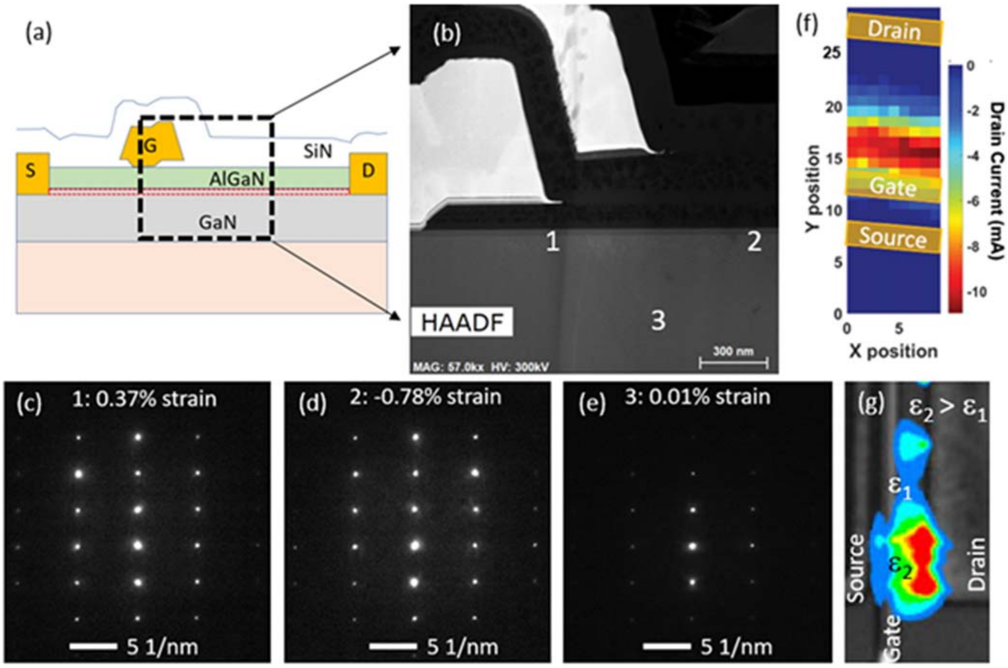

Figure 3. (a) Schematic of a GaN HEMT showing specific location for electron transparent specimen (b) High-angle annular dark-field image of the specimen with three numerically marked locations and their (c)–(e) corresponding nanodiffraction patterns. Also shown are the strain in the vertical direction. (f) Single event transient sensitive map of a HEMT, (g) Electroluminescence map of a HEMT showing non-uniformity of emission that could be ascribed to localized stress states. (parts of the figure from A. Khachatrian, N. J.-H. Roche, S. P. Buchner, A. D. Koehler, T. J. Anderson, D. McMorrow, S. D. Lalumondiere, J. P. Bonsall, E. C. Dillingham and D. L. Brewe,[55] reproduced with permission, copyright IEEE).

1995. There is also the JESD57 Test Standard, "Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy-Ion Irradiation," published in 2017, which is currently in the revision stage.[82] This standard defines the conductions for ground simulation and SEE and testing and is valid for a cyclotron or Van de Graaff accelerator provision of the heavy ions. The devices under test must be de-lidded and is valid for ions with atomic number $Z > 2$. It does not apply to SEE testing that uses protons, neutrons, or other lighter particles. The revisions currently being considered are to update the newer higher energy facilities capabilities, beam angle of incidence parameter, and SEB testing.[89]

JESD57 is the only U.S. test standard covering many of the heavy-ion induced single-event effects. Additional guidance can be found in the following:

(i) European Space Agency ESA-ESCC-25100 for SEE Test Method and Guidelines, issued in 2014.
(ii) ASTMF1192 Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices, issued in 2011
(iii) Sandia National Laboratory SAND 2008–6983PRadiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Test Guideline for Proton and Heavy Ion SEE, issued in 2008
(iv) NASA/DTRA, Field Programmable Gate Array (FPGA) Single Event Effect (SEE) Radiation Testing, issued in 2012.

Conclusions

Spacecraft electronics are susceptible to radiation effects that arise from interactions with these energetic particles—both degradation and eventual failure—due to total ionizing dose (TID), displacement damage dose (DDD) and the SEEs due to the instantaneous response of the electronics to single ionizing particles. If electronics are not "hardened" to both cumulative and single-event radiation effects, they will likely experience these effects in space, resulting in performance anomalies. Some radiation data are available from microelectronics vendors, from NASA's Jet Propulsion Laboratory and Goddard Space Flight Center, the European Space Agency, and in various data workshops associated with conferences on radiation effects, such as the Institute of Electrical and Electronics Engineers (IEEE) Radiation Effects Data Workshop. Use of these data poses challenges in that some results may be application specific and not generally valid since the product life cycles for commercial parts are so short that data may have little value soon after they are published; The sheer number of different commercial parts and technologies make it unlikely that a specific commercial device will have been tested previously.

While it has proven relatively straightforward to establish the TID and DD response of SiC and GaN devices,[15–18] SEE testing is much more complex and expensive, requiring exposure to a range of heavy ion beams.[20–53] Methods to provide more convenient and fast turn-around testing of such effects using X-rays or lasers are promising and provide much insight,[54–58] but do not fully replicate the energy deposition conditions of heavy ions.[57] Recent data in GaN has shown that the ion tracks associated with high LET values contain point and extended defects,[63] but that a strong recrystallisation effect induced by the ions significantly reduces the expected damage levels. The same type of study needs to be performed for SiC and also the effect of these ion damage tracks on device performance established. The accumulation of radiation damage is observed to a dynamic phenomenon proceeding via migration and interaction of point defects ballistically generated in collision cascades.[90,91] The dynamic annealing of radiation-induced defects is poorly understood in the wide bandgap semiconductors. The primary defects are mobile at normal temperatures and they undergo numerous types of interactions, including the self-annihilation of vacancies and interstitials, defect clustering or trapping at surfaces, interfaces, extended defects, and impurity complexes.[90] Data from Xe irradiation of Si indicates that the time constant of defect relaxation strongly depends on both ion energy and the depth from the surface.[90] It is very challenging to accurately model these processes due to the times scales involved and the limited understanding of the complex.[92] interactions between defects.

What are some of the open questions that need more work?

1. More studies examining the near-threshold region for SEB observed in ion beam experiments, especially utilizing laser or X-ray systems for pristine and irradiated devices. This might include examination of the bias dependence at the same laser pulse energy to keep a constant deposited charge. If there is a degradation it would change this bias dependence and affect the collected charge. Degradation would be evident in a change in collected charge as a function of bias.
2. Does single-event leakage current (SELC) also occur in GaN snd ultra wide bandgap semiconductors such as Ga_2O_3?
3. Does SiC exhibit the extensive recrystallization along heavy ion tracks seen in GaN?
4. What are the effects of ion energy and defect cascade density on the damage accumulation in SiC and GaN?
5. Is temperature a significant factor for SEE results in SiC and GaN?
6. What is the orbital equivalence of terrestrial tolerance experiments and should more mixed radiation testing be employed?[86]
7. What are the relative contribution of oxide damage vs semiconductor effects in MOSFETs during ion testing?
8. What is the effect of burn-in on SEE testing?
9. Is there a synergistic effect between dose and SEE?
10. What is the worst case ion condition for SEE testing?
11. Since ion range has a strong influence in SEGR and in that case LET doesn't fully capture the maximum energy deposition, do we need a revised standard?
12. Does gate stress exacerbate dose or ion effects?
13. Are there any device specifications or non-destructive tests of material properties that could indicate susceptibility to radiation effects?
14. Can alternative SEE testing approaches using lasers be made to more closely simulate high energy ion impingement?
15. Can athermal annealing methods provide a significant degree of damage removal in SiC and GaN, especially in devices with thick active regions.

The increasing use of small-satellites and large constellations that require high performance, small form factors and radiation resilience, along with high altitude and space-borne observatories, means we need a more sophisticated understanding of radiation effects, especially those due to single event effects.

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