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Radiation Damage in the Ultra-Wide Bandgap Semiconductor Ga_2O_3

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We present a review of the published experimental and simulation radiation damage results in Ga₂O₃. All of the polytypes of Ga₂O₃ are expected to show similar radiation resistance as GaN and SiC, considering their average bond strengths. However, this is not enough to explain the orders of magnitude difference of the relative resistance to radiation damage of these materials compared to GaAs and dynamic annealing of defects is much more effective in Ga2O3. It is important to examine the effect of all types of radiation, given that Ga₂O₃ devices will potentially be deployed both in space and terrestrial applications. Octahedral gallium monovacancies are the main defects produced under most radiation conditions because of the larger cross-section for interaction compared to oxygen vacancies. Proton irradiation introduces two main paramagnetic defects in Ga₂O₃, which are stable at room temperature. Charge carrier removal can be explained by Fermi-level pinning far from the conduction band minimum due to gallium interstitials (Gai), vacancies (VGa), and antisites (GaO). One of the most important parameters to establish is the carrier removal rate for each type of radiation, since this directly impacts the current in devices such as transistors or rectifiers. When compared to the displacement damage predicted by the Stopping and Range of Ions in Matter(SRIM) code, the carrier removal rates are generally much lower and take into account the electrical nature of the defects created. With few experimental or simulation studies on single event effects (SEE) in Ga₂O₃, it is apparent that while other wide bandgap semiconductors like SiC and GaN are robust against displacement damage and total ionizing dose, they display significant vulnerability to single event effects at high Linear Energy Transfer (LET) and at much lower biases than expected. We have analyzed the transient response of β -Ga₂O₃ rectifiers to heavy-ion strikes via TCAD simulations. Using field metal rings improves the breakdown voltage and biasing those rings can help control the breakdown voltage. Such biased rings help in the removal of the charge deposited by the ion strike. © 2022 The Electrochemical Society ("ECS"). Published on behalf of ECS by IOP Publishing Limited. [DOI: 10.1149/2162-8777/ ac8bf71

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Radiation damage in wide bandgap semiconductors is attracting increasing interest, especially in GaN.^{1–16} Recently, it has become clear that β -Ga₂O₃ is attractive for high temperature applications in harsh environments that cannot be tolerated by conventional electronics.^{17–29} Its wide bandgap allows operation at elevated temperatures, while it is also radiation hard and may provide improved performance over GaN.^{26,30–42} Radiation tolerance is an important factor while fabricating microelectronics and typical radiation damage suffered includes total dose effects, displacement damage, and single event effects.^{43–65} While significant work has been done for radiation effects in GaN^{1–16,59} and SiC,^{43–58,60–65} the understanding of carrier removal rates, defect levels and annealing regimes for Ga₂O₃ is on-going.^{66–72}

Spacecraft operating beyond Earth's magnetosphere are subject to space weather including the solar wind, a flux of radiation and charged particles that can degrade electronics.⁷³ These charged particles from the solar wind are also trapped inside the Earth's magnetosphere, forming the Van Allen radiation belts, which further expose transiting spacecraft to concentrated levels of charged particles and high-energy radiation.⁷³ An understanding of the radiation damage introduction mechanisms and the damage thresholds in terms of flux, radiation type and energy is needed for next

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generation semiconductors that will comprise the electronics and sensors capable of operation in harsh environments. 73

There are an increasing number of radiation-hardened components now made out of wide and ultra-wide bandgap semiconductors because it helps in reducing the size and weight and improves the computation speed. The global radiation-hardened electronics for space applications market is estimated to reach \$4.8 billion in 2032 from \$2.4 billion in 2021, at a growth rate of 1.70% during the forecast period. The growth in the global radiation-hardened electronics for space applications market is expected to be driven by increasing demand for communication and Earth observation satellites. Over the past few years, there has been a drastic shift toward adopting small satellites over conventional ones. Moreover, the market has been witnessing a drift in the trend from using small satellites for one-time stints toward their regular use in satellite constellations. With the rapid growth in small satellite constellations for various applications such as Earth observation, remote sensing, and space-based broadband services, the demand for radiationhardened electronic components has also significantly increased. Several projects are currently in progress to produce advanced radiation-hardened electronics with enhanced capability to shield space perturbations at low cost, which are expected to increase with the launch of upcoming mega-constellations as well as with the rising interest of companies in satellite components that can sustain in the harsh space environment for longer period of time.

Wide-bandgap semiconductor (e.g. GaN and SiC currently and potentially Ga_2O_3 in future) devices are increasingly used in space and defense systems for embedded high-performance computing and

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Figure 1. Lattice structure of the three main polytypes for Ga₂O₃.

high-throughput I/O processing.^{17-19,74-84} A critical issue for many devices is the transient ionization-induced processes associated with high linear energy transfer (LET) particles and intense pulses of photons. The confined dimensions (<10 nm radius in the case of charged particles), short time frame (0.1 to 100 ps) and extreme temperatures (1000 to 10,000 degrees) of the ionization-induced thermal spike defy simple dynamics or thermally activated descriptions yet can impact defect production and device degradation. Even the strike of a single ion can produce free charges and defects through ionization in the electrical devices, which can permanently (or temporarily) disrupt device functionality. The effects of ionizing radiation on electronics result from phenomena that occur across time and length-scales. Modeling and simulation approaches provide a range of tools across the scales that can be used to understand the impact of radiation. Defect generation and charge transition are the fundamental mechanisms that govern radiation effects and mitigation in electronic materials.⁸

Defect production may vary depending on the type of radiation, from high energy ion irradiation and intense pulsed laser irradiation to simulate SEEs from cosmic/solar radiation or intense X-ray bursts. Measuring the response of wide bandgap materials to single-ion events is extremely challenging and two experimental approaches are generally employed (i) measurement of the material response to a large number of non-overlapping ion events of identical energy to obtain an average response or damage state for ions of specific energy; and (ii) direct measurement of material response to single-ion events, one ion at a time. At low ion fluences (between 10^{10} and 10^{12} ions cm⁻², depending on ion energy and mass), damage regions from individual ions do not overlap and the response to ions of specific mass and energy can be characterized using the known density of ion events and a variety of techniques to determine the nature and concentration of damage/defects.

Polytypes of Ga₂O₃.—While most attention has concentrated on the thermodynamically stable β -Ga₂O₃ phase since it can be grown both as single crystals and in epitaxial form and can be alloyed with Al or In to modulate bandgap, there are two other polytypes of interest.^{17–20} The lattice structures of the three most useful polytypes are shown schematically in Fig. 1. The bandgap of the α -polytype (5.2 eV) is larger than that of the β (4.9 eV) drawbacks and does not have the

asymmetric thermal conductivity and electrical and optical properties of the latter. Similarly, the ε -polytype is ferroelectric and has a high spontaneous polarization, attractive for achieving high 2-dimensional electron gas density. There is much less known about the response of these other two polytypes to radiation, especially the ε -polytype.²⁰

For studying the effects of radiation, we have generally employed either thin films or vertical rectifier structures as our standard device platform, since these enable measurements of most parameters of interest in quantifying the effects of damage.^{95–103} A typical rectifier structure is shown in Fig. 2. It consists of a thick, lightly doped epitaxial layer grown on a conducting substrate. Edge termination generally consists of a dielectric overlap at the edge of the rectifying contact.

Simulation Methodology

A TCAD model of a rectifier structure was used to solve for the electric field distribution and impact ionization using Synopsys Sentaurus structure and device simulator. The device structure was first simulated for breakdown, and experimental data was used to validate the models used in this study. To simulate the reverse leakage and the eventual breakdown, modeling done by Lingaparthi et al.¹⁰⁴ and Labed et al.¹⁰⁵ is used as the basis for our simulations. The top Schottky contact was given the Schottky boundary condition and barrier tunneling is turned on to simulate the thermionic field emission under high reverse bias. A nonlocal tunneling model¹⁰⁶ as given by the local tunneling generation rate (Eq. 1), using the tunneling probability calculated using the WKB approximation. Other models include an optimized Arora model for mobility, an impact ionization model based on the van Overstraeten de Man model (Chynoweth model),¹⁰⁶ a simple



Figure 2. Schematic of vertical Ga_2O_3 rectifier structure used for radiation studies.



Figure 3. Schematic of two main mechanisms by which Ga_2O_3 degrades upon irradiation-removal of carriers to traps and reduction of carrier mobility by introduction of additional charged defects.



Figure 4. (top) Calculated cross-section for electron (e) irradiation with Ga or O atoms in Ga_2O_3 , as a function of electron energy.(bottom) calculated cross section as a function of threshold energy.

band-to-band tunneling model, and Shockley-Read-Hall (SRH) recombination and generation.¹⁰⁷ These models maintain the concentration of charge carriers and help with convergence, and the parameters used in these models are based on values obtained from previous studies or calibrated for this work. We simulated the transient response vs strike depth (strike at edge of Schottky) as a function of the number of rings (n = 0–2) at constant spacing of 4 or 10 μ m; ring voltage to gate



Figure 5. Energy loss profiles for protons of 20 MeV or 1 GeV energy in Ga_2O_3 , calculated from SRIM.



Figure 6. Electronic and nuclear stopping powers for ${}^{1}\text{H}^{+}$ over a broad energy range in Ga₂O₃ calculated from SRIM.

voltage ratio of 0.95, depth vs ring spacing and bias ratio on the rings, the strike position vs number of rings bias ratio and also ring spacing.

For the SRIM simulations, we used different values of the displacement energy of O and Ga to examine the energy dependence of vacancy creation.



Figure 7. LET for Ga_2O_3 with ¹H as a function of energy. The LET is the surface value due to ionization loss in the SRIM simulations.

Experimental Methodology

We used rectifier structures described elsewhere^{82,86} and shown in Fig. 2 as the device platform for measuring carrier removal rate. These devices wee exposed to various fluences of 100 keV –10 MeV protons, 1 MeV electrons, fast reactor neutrons, 10 MeV alpha particles or Co-60 gamma rays from various sources. We also measured minority hole diffusion length and lifetime measured by Electron Beam Induced Current (EBIC) and Time-Resolved cathodoluminescence (CL).

Results and Discussion

Total dose damage.—Since Ga₂O₃ devices and more generally all wide bandgap semiconductor devices normally use metal gates, Total Ionizing Dose (TID) effects are not as important as they are in Si technology,^{40,66–70} which is based on MOS-gate devices. The relations between charge (e) and electric field, E (Poisson's equation) and the transport (drift/diffusion) equations depend on carrier mobility ($\mu_{e,p}$) and density (n,p), i.e.,

$$J_n = e\mu_n nE - ED_n \nabla n$$
$$J_p = e\mu_n pE - ED_p \nabla p$$

The current, I, in a rectifier is given by,

$$I = I_0 (e^{\frac{eV}{nkT}} - 1)$$

While the similar expression for a lateral field effect transistor is the current between source and drain is given by,

$$I_{DS} = Wen_s v(x)$$

where W is the channel width, n_s is sheet carrier density and v(x) is carrier velocity at position x.

Note that in both the lateral and vertical devices, the current depends on carrier concentration and mobility. Displacement damage from radiation creates traps that remove carriers from the conduction process and degrade mobility, i.e., n, μ are reduced. These mechanisms are shown schematically in Fig. 3.

Radiation-induced defects.—A useful parameter for comparing the relative amount of change in electrical properties in irradiated semiconductors is the carrier removal rate, R_C , defined by:^{40,66–68}

Irradiation Details:





Figure 8. Temperature dependence of diffusion length in lightly p-type Ga_2O_3 before and after irradiation with protons at a cumulative dose of $\sim 7 \times 10^{14}$ cm⁻².

$$R_{\rm C} = (n_{\rm s0} - n_{\rm s})/\Phi$$

where Φ is the proton fluence, n_{s0} is initial carrier concentration, and n_s is the irradiated carrier concentration.

The concentration of created vacancies N_V given by,

$$N_{VGa} = \sigma_{Ga} N_{Ga} \Phi$$
$$N_{VO} = \sigma_O N_O \Phi$$

where $\sigma_{Ga/O}$ are the cross sections for ion interaction with the lattice ions, $N_{Ga/O}$ are the concentrations of the corresponding lattice ions, and Φ is the fluence, i.e., the number of ions per unit area of the sample. An example calculation for cross-sections of Ga and O atoms to electron irradiation of different energy is given in Fig. 4 (top). Note that for most energies, there will be mainly Ga atoms displaced, i.e. creation of Ga vacancies, $V_{Ga}^{108,109}$ We used a value of 20 eV for the threshold displacement energy. The variation of cross-section with the threshold value is shown at the bottom of Fig. 4.

Oxygen vacancies V_O in Ga_2O_3 predicted to be deep donors, whereas Gallium vacancies V_{Ga} are predicted to be deep acceptors.^{17–20} On the basis of the $\sigma_{Ga/O}$ -Ee data in Fig. 4, we expect ion irradiation with energy less than 0.5-MeV would exclusively produce donor-type doping by oxygen vacancies. For >2.5–MeV beam energy, irradiation simultaneously produces V_{Ga} and V_O . The rate of creation of V_{Ga} is about twice that of V_O . The formation energy of V_{Ga} is sufficiently low for it to be incorporated in sizeable concentrations during growth, particularly under O-rich and n-type conditions.^{17–20} The thermodynamic (2-/3-) transition levels of the five different V_{Ga} configurations are predicted between E_{C} - (1.7–2.6)eV. V_{Ga} can form stable complexes with shallow donor impurities such as H and Si_{Ga} and the V_{Ga} -2H complex has been assigned to an IR absorption line 3436 cm^{-1,92} Complexing V_{Ga} with shallow single donors will successively passivate its acceptor levels, shifting luminescence to higher energies.



Figure 9. Normalized room-temperature cathodoluminescence spectrum (top) before and (center) after proton irradiation. A slight blue shift of the irradiation peak with smaller full width at half-maxima was observed after irradiation. After subsequent electron injection for 20 min (bottom) there is evidence of athermal defect annealing.

Energy deposition and range parameters.—A sometimes-confusing aspect of radiation damage in semiconductors is that a different terminology is employed for the same quantities. Linear Energy Transfer (LET) is used for total or electronic stopping power. For protons and other ions, the Total Ionizing Dose (TID) is equal to the product of LET and fluence. For MeV and GeV charged particles, the two are essentially the same. Similarly, what is commonly termed the Non-Ionizing Energy Loss (NIEL) is the same thing as Nuclear Stopping Power used by ion implantation specialists.

The range and resulting ion distribution are calculated by a number of codes, one of the most common being Stopping and Range of Ions in Matter (SRIM).¹¹⁰ Figure 5 shows the calculated

energy loss profiles for protons of 20 MeV or 1 GeV energy in Ga₂O₃. Note at these energies, the protons will completely traverse the thickness of a normal Ga₂O₃ substrate (~750 μ m). The electronic and nuclear (NIEL) stopping powers of Ga₂O₃ to protons up to 1 GeV energy are given in Fig. 6. Note that the ionizing (electronic) energy loss is dominant over this entire range of energies. NIEL, often called Displacement Damage (DD) depends on the particle fluence Φ (number of ions cm⁻²). The units of NIEL are (keV-cm² g⁻¹) and the DD dose is given by the product of NIEL × Φ .

Figure 7 shows the LET as a function of proton energy in Ga_2O_3 , calculated from SRIM. Note how this falls rapidly with proton energy, which is the basis for the utility of protons being used to deliver energy to spatially limited locations within electronic devices. This is used in device isolation schemes and in irradiation of tumors while minimizing damage to areas around the tumor.

Effects of proton irradiation of Ga_2O_3 .—Changes in the diffusion length of a semiconductor are a sensitive indicator of the presence of radiation damage.^{111,112} Electron Beam-Induced Current (EBIC) and Cathodoluminescence (CL) measurements can characterize the diffusion length (L) of minority carriers (electrons) and luminescence behavior of such samples, respectively. Nominally p-type Ga₂O₃ samples were irradiated with protons having a dose/energy sequence to create a near-uniform hydrogen concentration around 10^{19} cm⁻³. This consisted of 25 keV/1.6 × 10^{14} cm⁻², 50 keV/1.7 × 10^{14} cm⁻² and 70 keV/3.6 × 10^{14} cm⁻². The temperature dependence of L before and after proton irradiation is shown in Fig. 8. Within the current temperature range of measurements, it is likely that the origin of L decrease is due to mobility degradation due to phonon scattering.

Figure 9 shows normalized room temperature CL spectra before and after proton irradiation and after subsequent electron injection from an electron beam. The initial creation of vacancies produces some reduction in strain-induced broadening, while there was no additional change after the electron injection, but the latter was accompanied by an increase in carrier lifetime, indicating athermal annealing of radiation defects.

Summary of radiation trap states and carrier removal rates in β -Ga₂O₃.—Figure 10 summarizes report trap states for as-grown and irradiated β -Ga₂O₃. These include the position of these states in the bandgap and the possible identification of the origin of the traps. Note the importance of V_{Ga} related states. After irradiation, it is observed that the concentration of some of the defects present in the as-grown material increases, suggesting the contained vacancy-related defects to begin with.^{71,107,713-135}

A summary of carrier removal rates is given in Fig. 11 (top) for irradiated β -Ga₂O₃. The removal rates are highest for alpha particles, followed by protons, neutrons, electrons and gamma rays. This is in general agreement with the relative amount of NIEL associated with each type of radiation. Electron removal rates at low proton energies are usually much lower than predicted based on SRIM calculations of the Ga vacancies densities, presumably because of the dynamic annealing. For energies ~10–20 MeV experimental values are close to calculated. At very high proton energies the actual removal rates are higher than predicted.

The removal rates for β -Ga₂O₃ for protons and neutrons are on par with those reported for GaN and SiC, as shown for the example of GaN and related alloys in Fig. 11(bottom). Since the differences with Si would be less than a factor of 2 based purely on threshold energies for displacement, the presence of strong dynamic annealing in the wide bandgap semiconductors must be invoked and is consistent with the known diffusivity of primary point defects in these materials at and above room temperature.

TCAD simulations of heavy ion strikes and preliminary charge collection-Experiments in β -Ga₂O₃.—SiC and GaN power devices are susceptible to degradation from single event effects (SEE)







Figure 11. Summary of carrier removal rates for irradiated (top) β -Ga₂O₃ and (bottom) GaN.

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,



Figure 12. Hole concentrations in the device with (top) one concentric field ring as a function of time starting from 10^{-13} (ion-strike) to 10^{-6} s. The device with 1 ring is faster at charge removal compared to a (bottom) device without rings.

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. 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 nondestructive and destructive. The destructive single event effects are single event burnout (SEB), single event gate rupture (SEGR), and single event dielectric rupture (SEGR). SEB and SEGR are different mechanisms, but they can be hard to distinguish. SEB generally refers to what happens in a power MOSFET when ionization causes the breakdown voltage to be exceeded and the radiation-induced high current may causes catastrophic damage to the device. In other words, single-ioninduced strike causes a localized high-current state, which may result in catastrophic device failure, and is normally characterized by a significant increase in drain current that exceeds the device rating. However, basically nothing is known about SEE in Ga₂O₃.

We have performed some preliminary TCAD simulations of charge collection response to a heavy-ion strike and the resulting single effect burnout on β -Ga₂O₃ Schottky diodes with biased field rings.¹¹³ The charge removal after simulated heavy-ion strikes was greatly improved with these field rings.¹¹⁴ The breakdown of rectifiers occurs near the contact edge where the electric field is the highest during the voltage blocking operation and device failure is usually triggered here Fig. 12 shows that when using concentric field rings, the current drops to zero faster, whereas with no rings there is a residual charge removal, while the smaller spacing between rings also removes the charge faster. Both the position of the strike and the LET value influence the



Figure 13. Simulated transient response to a heavy-ion strike at various positions in a rectifier structure, with two concentric field rings, a depth of ion strike of 4um and ratio of bias applied on outermost ring contact to next inner contact Vr/Vg = 0.95.

charge removal rate. An example is shown in Fig. 13. These simulations clearly show that use of biased rings greatly improves both the breakdown voltage of the device and the charge removal after simulated heavy ion strikes, showing a pathway to use device design to partially mitigate single event effects in β -Ga₂O₃ power rectifiers. Some preliminary experimental data has also been generated by mapping the spatial dependence of laserinduced transient shapes. Location-specific changes in the shape of the transients and the amount of collected charge provide insight into trap formation and charge-collection mechanisms. A pulsed laser is used to generate spatial plots of single event transient (SET) amplitudes and collected charge, from which regions of enhanced SET signals, or "hot spots," are identified. These hot spots are attributed to the presence of lattice defects that modify the local electric field, particularly in the sourcedrain, region near the edge of the gate where the transient sensitivity is greatest.

Single event errors (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 as the ion travels through a material, expressed as MeV/(mg cm⁻²) or 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

Figure 14 shows an example of a charge collection waveform for laser irradiation of a Ga_2O_3 rectifier, along with the collected charge as a function of laser energy. These fundamental studies will help elucidate charge collection dynamics in Ga_2O_3 devices.



Figure 14. (top) Single event transient waveform for 250 pJ laser irradiation at 350 nm, with the rectifier biased at 40 V (bottom) collected charge as a function of 350 nm laser energy. Laser charge deposition takes place via two-photon absorption process.

Summary and Conclusions

While there has been significant progress in understanding radiation damage effects in Ga_2O_3 , these are questions that need additional research:

- a) Is there a synergistic effect between total dose and SEE in Ga₂O₃, through increased off-state leakage due to cumulative ion strikes below disruption threshold?
- b) what is the effect of mixed radiation environments more typical of what Ga₂O₃ avionics will encounter?
- c) what is the effect of temperature on SEE response in Ga_2O_3 ?
- d) what is the role of hydrogen, either in gate dielectrics or in forming defect-H complexes?^{113,115–118}
- e) are there any Ga₂O₃ device specifications (e.g., the electric field profile, contact metal) that act as "predictors" of more severe radiation effects?
- f) does electrical aging increase susceptibility to radiation-induced failure in Ga₂O₃?
- g) what are the threshold displacement energies for each type of radiation for Ga₂O₃?

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