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TECHNICAL REPORT

Fundamental Studies and Modeling of Radiation Effects in beta-Gallium Oxide

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14. ABSTRACT We completed a detailed study to understand the low and high dose stability of Gallium Oxide to neutrons, electrons and protons, in order to simulate common radiation environments. Our method was to use a unique coupling of theory and experiment to produce a detailed understanding of radiation on this new ultra wide bandgap semiconductor and a predictive capability for new radiation hardened materials and components.						
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DTRA Basic Research Final Report

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Organization/Institution: University of Florida

Project Title: Fundamental Studies and Modeling of Radiation Effects in β -Ga₂O₃

What were the major goals of the project?

To understand the stability of β -Ga₂O₃ to neutrons, gamma rays, electrons and protons, in order to simulate common radiation environments. Measure fundamental parameters such as carrier removal rate, energy level and thermal stability of traps and role of hydrogen. The project consists of a unique coupling of theory and experiment designed to produce a detailed understanding of the effects of radiation on this promising wide bandgap semiconductor and a predictive capability for new radiation hardened materials and components.

What was accomplished under these goals?

1. Major Activities:

We established the following

- (i) The radiation damage region contains carrier traps that reduce the conductivity and mobility of the Ga₂O₃ and at high enough doses, severe degradation of rectifier devices
 - (ii) Point defects create traps, ionized traps create reductions in electron mobility, negative trapped charge and decrease in carrier density.
 - (iii) Neutron irradiation creates disordered regions in the Ga₂O₃, while the displacement damage from the other forms of radiation is more typically point defects.
 - (iv) Carrier removal rate is highest with alpha particles, followed by protons, electrons and neutrons in the following sequence, consistent with their average non-ionizing energy loss
 - (v) No detectable effect of electric field or hydrogen concentration in Ga₂O₃ on defect introduction rate or carrier removal rate.
 - (vi) Ga₂O₃ is several orders of magnitude more resistant to radiation damage than GaAs due to higher displacement threshold energy (Td) and empirical observation Td is inversely proportional to lattice constant.
 - (vii) The carrier removal rate in Ga₂O₃ for light particles is well accounted for by the introduction of simple defects.
- 2. Specific Objectives:** These included understanding the energy levels, carrier removal rate, thermal stability of radiation damage in Ga₂O₃-based materials, the role of defects on the subsequent amount of degradation caused by exposure to radiation damage, and finally, incorporation of these mechanisms into a predictive simulator.

3. Results

This final report provides an overview of radiation damage in β -Ga₂O₃, an ultra-wide bandgap semiconductor attracting interest for power electronics and solar-blind ultraviolet detection. Initial studies of proton, electron, neutron, gamma ray and alpha particle damage have been reported for Ga₂O₃. In displacement damage measurements, the carrier removal rates are highest for alpha particles ($\sim 10^3$ cm⁻¹) and the lowest for gamma rays (~ 1 cm⁻¹). Deep electron and hole traps are created, leading to reductions in minority carrier diffusion length and lifetime. Compensation of shallow donors by gallium vacancies interacting with hydrogen is one of the main carrier loss mechanisms resulting from proton damage. Using rectifiers as a platform for studying radiation effects in β -Ga₂O₃ under conditions relevant to low earth orbit of satellites shows the carrier removal rates for proton, electron and neutron irradiation are comparable to those in GaN of similar doping levels. The main defect created in Ga₂O₃ by proton irradiation is a relaxed V_{Ga}-2H center (Ga vacancy with two hydrogens attached). Electron Paramagnetic Resonance (EPR) after irradiation also shows one dominant paramagnetic defect, which has the characteristics of a V_{Ga}-related center. There have been few studies of total ionization dose or single event upsets in Ga₂O₃ and while the former is not expected to be significant because of the lack of gate oxides in most device structures in this materials system, single event upsets may be an issue.

There is a strong interest in electronics capable of operation in the harsh environment of space, as well as in terrestrial radiation applications monitoring reactors or stored nuclear waste⁽¹⁻⁹⁾. In the space radiation environment, there are the Van Allen radiation belts, containing protons with energies up to 500 MeV, as well as electrons up to 10 MeV⁽¹⁻⁴⁾. The fluences of these particles depend on the solar activity^(2,3). Solar flares produce protons up to 500 MeV and a smaller component of heavy ions up to 10 MeV/nucleon. These are prevalent in the slot region between the main Van Allen belts⁽¹⁻⁶⁾. Finally, there is a near-constant background of galactic cosmic rays consisting of protons and high charge and energy ions, up to 300 MeV/nucleon^(1,4). Solar flares may expel intense clouds of protons that deliver doses of 0.3-3 Gy/3 days, meaning roughly 50% of cells of crew members on proposed round trips to Mars would be traversed by at least one galactic cosmic ray with high charge and energy (HZE)⁽¹⁾. On the old Skylab missions, typical doses encountered by the crew and equipment were 0.025 Gy for orbits 250-300 km, at 10 mrad/day⁽¹⁻⁴⁾. Each pass through the Van Allen corresponds to 0.1-0.2 Gy/hr (passage lasts 10-20 min)⁽⁴⁾. On the space shuttle, the dose was 433 mrem/mission average skin dose. To put this in perspective, a CT scan represents 700 mrem/event, X-ray diagnostic 100-200 mrem/event and human natural sources (cosmic, radioactivity) 80 mrem/yr⁽¹⁾.

In terms of electronics, there are three main types of radiation damage in semiconductor devices.

1. Total Ionization Dose (TID), effects caused by long term exposure to ionizing radiation. These induce changes in electrical properties of materials that may cause them to operate incorrectly or fail. This is an important effect for insulators (charge build-up), cabling, electronics (surface charge effects), optical elements (lenses, filters) and cryogenics. Since Ga₂O₃ devices are typically not MOS-gate structures⁽¹⁰⁻¹³⁾, TID effects are not considered to likely be a significant issue.
2. Displacement Damage Dose (DDD) effects are due to long term exposure to interactions with non-ionizing energy transfers. These create displacement defects in semiconductors and introduction of traps deep in the bandgap. Since Ga₂O₃ has a high bond strength, it has a

threshold for DD effects several orders of magnitude larger than conventional semiconductors such as Si and even GaAs⁽¹⁰⁻¹⁹⁾.

3. Single Event Effects (SEE), an effect due to a single interaction involving transit of an ionizing particle through a device^(1,5). Single-event transients (SETs) are a potential reliability issue for devices in space-based rf and power systems⁽²⁰⁻²³⁾. SETs occur when incident ions, passing through or close to sensitive volumes in the device, interact with atoms in the semiconductor, liberating electrons that disturb voltages^(1,5,7). These take the form of voltage glitches, whose amplitudes and widths depend on bias conditions and strike location. SETs last on the order of picoseconds to nanoseconds. A recent addition to the probes available for investigating SETs in electronic devices is the pulsed, focused x-ray beam^(5,7). Similar to ions and to photons in the visible spectrum, x-rays passing through material also produce electron-hole pairs, but the energy-loss mechanisms involved are different. Both result in SETs, and an area of investigation is whether those produced by x-rays are similar to those produced by ions or pulsed laser light. An advantage of x-rays is their ability to penetrate metal over-layers and inject charge underneath the gate, something not possible with visible laser light^(5,7). SETs are important in digital circuits such as memories or microprocessors and induce errors, undesired latch-ups and possible system failure. This will likely be a problem in Ga₂O₃, as has been reported for AlGaIn-based High Electron Mobility Transistors (HEMTs) of even high Al content (>70%)⁽²²⁾. However, to this point, there have been no reported studies of single event effects in Ga₂O₃.

Displacement damage and total ionizing dose are cumulative effects, while single event upsets are stochastic effects, with the latter originating from the protons of solar flares and the radiation belts, as well as the ions from cosmic rays.

β -Ga₂O₃ has a bandgap of 4.8-4.9 eV and high critical electric field (E_c) strength of ~ 8 MV/cm¹⁰⁻¹⁹, allowing high temperature, high power device operation. The availability of large, melt-grown substrates at relatively low cost has suggested the possibility of SiC-like performance at Si-like cost^(15,16). Figure 1 shows the crystal structure of the β -polymorph, as well as a large diameter wafer cut from a bulk crystal grown by the edge defined, film-fed growth (EFG) method. The main electronics applications for β -Ga₂O₃ rectifiers and metal-oxide-semiconductor field effect transistors (MOSFETs) involve power conditioning and switching systems with low power loss during high frequency switching up to the GHz regime⁽²⁴⁾. Ga₂O₃-based photodetectors are attracting interest as truly solar-blind deep ultraviolet (UV) photodetectors with cut-off wavelength < 280 nm^{9,14,16,18}. These have applications in military systems, air purification, space communication, ozone-layer monitoring and flame sensing.

2. Basic Radiation Damage Measurement Quantities

There are a number of fundamental parameters used in radiation damage studies in semiconductors, which we define below^(20-23,25,26):

Flux(ϕ) is number of particles per unit area and per unit time,

$$\phi = \text{Particles}/(\text{Area} \times \text{Time})$$

The time integral of the flux is the Fluence(Φ) is number of particles per unit area

$$\Phi = \int \phi dt = \text{Particles.cm}^{-2}$$

The dose is the energy deposited by radiation per unit mass, which scales with fluence

$$D = E/M$$

A particle can transfer (deposit) energy in a semiconductor by ionizing energy loss, which is equivalent to total ionizing dose (TID) or by non-ionizing energy loss (NIEL), which is equivalent to the displacement damage dose (DDD). These are defined as follows:

TID = (energy to ionization)/ mass=LET $\times$ Φ , where LET is the linear energy transfer

DDD= (energy to displacements)/ mass=NIEL $\times$ Φ , where NIEL is the non-ionizing energy loss.

LET is the energy deposited per unit path length due to ionization; i.e. the Coulomb interaction of the impinging particle with the electrons of the material causing ionization, defined as $\Delta E_{\text{ionization}}/\Delta x \rightarrow \text{LET} = (dE/dx)_{\text{ionization}}$.

NIEL is the energy deposited per length unit due to non-ionizing interaction of the impinging particle with the nuclei of the lattice causing displacement damage, defined as $\Delta E_{\text{displacement}}/\Delta x \rightarrow \text{NIEL} = (dE/dx)_{\text{displacement}}$.

DDD = KERMA/ mass= NIEL $\times$ Φ , where KERMA is defined as the kinetic energy imparted by radiation into displacement, ie. total Kinetic Energy Released in Matter (silicon equivalent). Displacement damage is the result of transfer of non-ionizing energy to lattice nuclei, causing structural damage to lattice (defects) by collisions between incoming particles and a lattice nucleus displacing an atom from its original lattice position generating point defects (vacancies and interstitials).

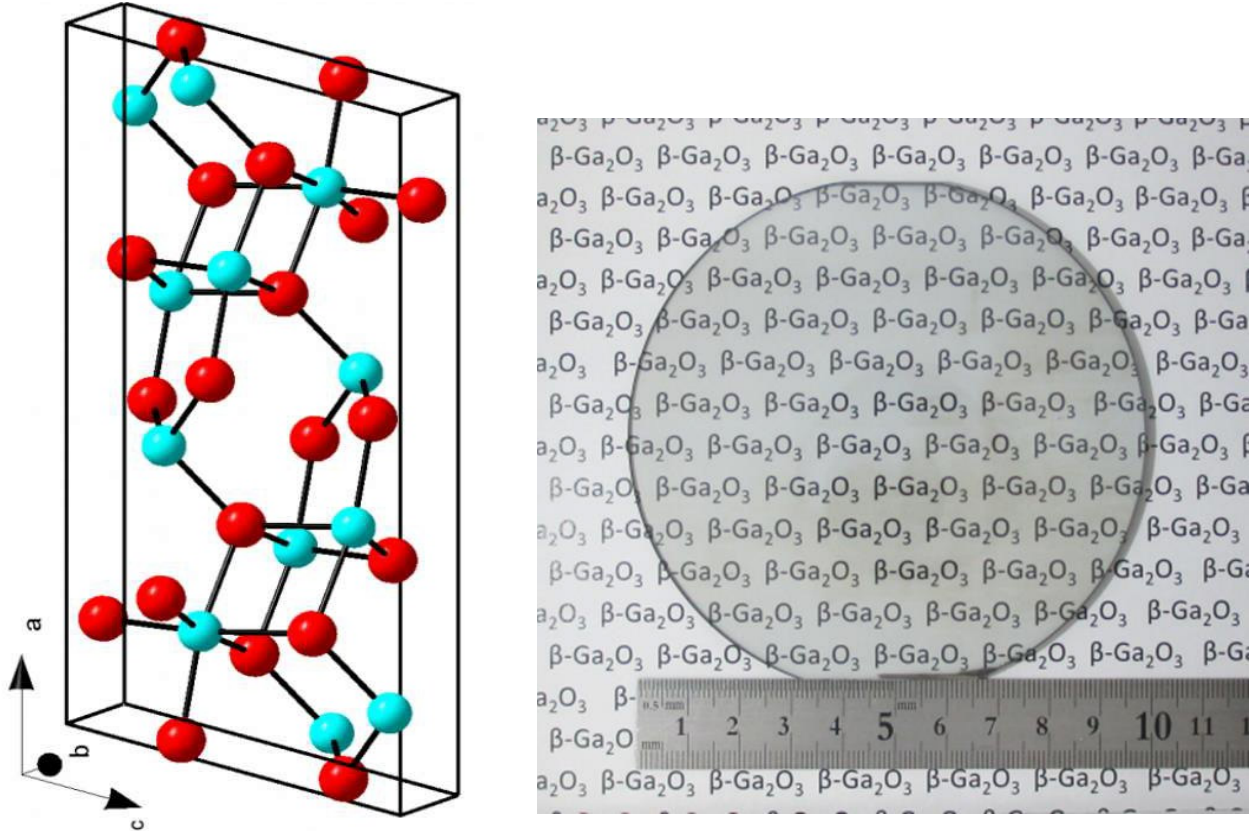


Figure 1. (right) β -Ga₂O₃ crystal structure and (left) large diameter wafer from EFG-grown crystal.

The energy deposited into a block of matter of a certain mass includes the energy to ionization (MeV)= LET (MeV.cm²/mg) $\times$ Φ (cm⁻²) $\times$ mass(g) $\times 10^3$ and the energy to displacements (MeV)= NIEL(MeV.cm²/mg) $\times$ Φ (cm⁻²) $\times$ mass(g) $\times 10^3$. Heavy ions lose a small amount of energy per

Coulombic collision and the total stopping power dE/dx is given by $dE/dx = (dE/dx)_{\text{ionization}} + (dE/dx)_{\text{nuclear coulombic}} = \text{LET} + \text{NIEL}$. Both of these quantities change along the ion track as the particle slows down. The displacement energy is manifested as lattice damage to the semiconductors, while the ionizing energy is lost as heat. Incident electrons and positrons may lose a large fraction of their kinetic energy in one collision and are easily scattered to large angles.

In single event upsets, locally, the ionization may be high inside single active/sensitive volumes ^(1,6,7,22). A high enough ionization may induce a single event effect. In space applications, electronic devices may receive direct impacts of HZE cosmic rays during the operational lifetime of a spaceflight. More frequently, energetic neutrons and protons may produce secondary highly ionizing ions. Neutrons are a problem in avionics and at sea level ^(1,21-23). The nature of the device determines the active volumes that may collect charge and the effect on performance when large amounts of charge are deposited.

Ga₂O₃-based UV photoconductors and electronic devices would be subject to fluences of high energy protons, alpha particles and electrons in low earth orbit satellites, as well as neutrons or gamma rays in radiation-hard nuclear or military systems ⁽²⁷⁾. Each type of radiation produces different types of lattice damage. At high incident energies, the energy of the primary recoils produced by collisions with lattice atoms becomes high enough to give rise to collision cascades and form disordered regions with high defect density in the core. The collision between an incoming ion and a lattice atom displaces the atom from its original lattice position, leading to vacancies, interstitials and complexes of both, and potentially with impurities in the Ga₂O₃ ⁽²⁷⁻³¹⁾. If an incident energetic particle such as a neutron or proton collides with the nucleus of a lattice atom, the primary knock-on atom may be displaced from the lattice if the incident particle has sufficient energy ($E > E_d$), where E_d is the lattice displacement energy ^(25,26).

3.Importance of Radiation Damage in Electronics

Most telecommunications satellites are in geosynchronous orbit, at the outer edge of the second Van Allen radiation belt ^(3,4). Most navigation satellites operate in medium Earth orbit and pass through the heart of that outer radiation belt where they may experience much higher levels of radiation ^(3,4). Most Earth-observation satellites operate in low Earth orbit and may experience higher radiation levels if their orbits traverse the South Atlantic Anomaly or the auroral zones ^(3,4). The variability in flux of relativistic electron ($E > 1$ MeV) in the radiation belts is caused by changes in the solar wind by activity on the Sun.

While Ga₂O₃ is not yet used in commercial or government satellites, it is not expected that TID or NIEL will be issues, because the devices do not employ MOS gates and also because of the high bond strength ⁽²⁷⁾. However, recent experiments on high Al-content AlGaN shows that single event upsets are an issue there ⁽²²⁾ and one might reasonably expect similar issues with Ga₂O₃, although the low hole mobility may mitigate this somewhat ⁽³⁰⁻⁴⁰⁾. Even in shielded environments, there is a low energy proton spectrum that creates single event upsets, resulting in data corruption, and transient disturbance. Within the family of Single Event Upsets phenomena, there are classical events that cause a change of state in storage elements, while Single Event Functional Interrupts (SEFI) produce temporary loss of device functionality and may be recovered by reset.

It is important to note that the range of high energy protons is much larger than the thickness of typical devices, so even with packaging and any shielding, the ions traverse the entire volume of the device. Figure 2 shows the projected range of protons and alpha particles in Ga₂O₃ as a function of energy ⁽²⁰⁾. Typical active layer thicknesses in Ga₂O₃ devices are <20 μm .

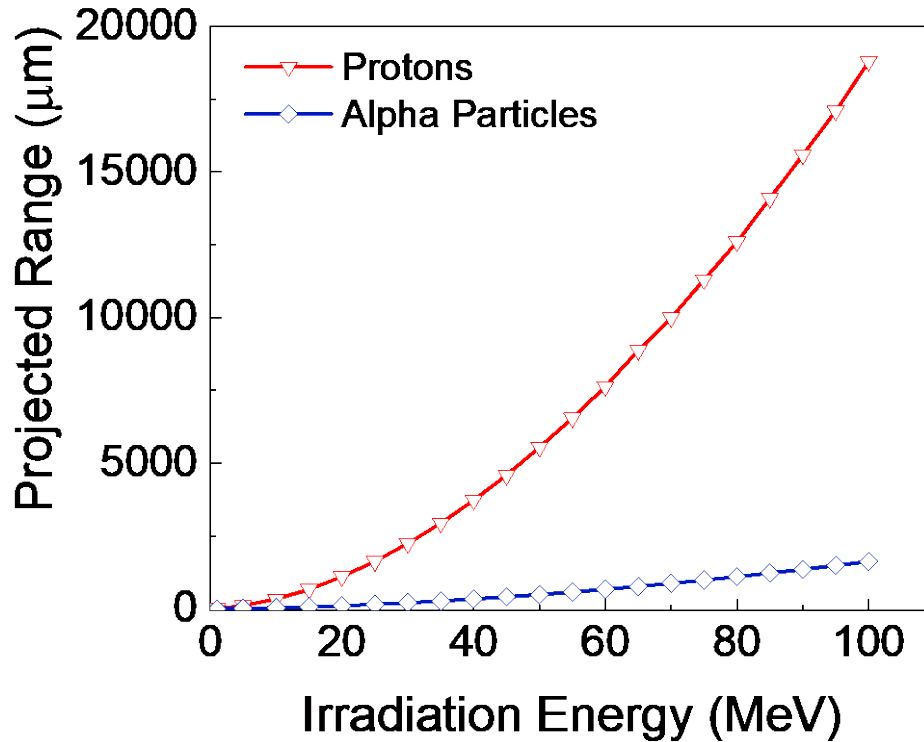


Figure 2 Range of protons and alpha particles in Ga₂O₃ as a function of energy (1-100 MeV).

4. Radiation Damage in Wide Bandgap Semiconductors

It is well established that Ga₂O₃ is between 1-2 orders of magnitude more radiation-hard than Si in terms of NIEL with protons. By this, it is meant that for exposure to fluences of the same proton energy, a Ga₂O₃-based device will last 10-100 times longer than a Si device⁽²⁷⁾. The wide bandgap and ultra-wide bandgap semiconductors, which include GaN, SiC, AlN, diamond, BN, Ga₂O₃ all have high bonding energies, which means a lower number of primary defects for a given energy deposition⁽⁴¹⁾. The atomic displacement energy has been measured in many semiconductors and empirically determined to be inversely proportional to the volume of the unit cell^(1,8,25,26). β-Ga₂O₃ has been suggested to have similar and perhaps even improved radiation tolerance than GaN based on slightly higher displacement energies for Ga and O of 25 eV and 28 eV in β-Ga₂O₃, respectively, compared to 20 eV and 10-20 eV for Ga and N in GaN, respectively^(24, 42,43).

The stability of primary radiation defects in Ga₂O₃ is still being established⁽⁴⁴⁻⁶⁴⁾. High energy particle irradiation produces a dominant paramagnetic defect assigned to gallium vacancies (V_{Ga}), with the structure of a hole on an O atom adjacent to a cation vacancy. Korhonen et al.⁽³²⁾ estimated a V_{Ga} concentration of at least $5 \times 10^{18} \text{ cm}^{-3}$ in even as-grown undoped samples. Since theoretical calculations predicts that these V_{Ga} should be in a negative charge state for n-type samples⁽²⁸⁾, they will compensate the n-type doping. Kananen et al.^(33,34)

showed from electron paramagnetic resonance (EPR) that doubly ionized (V_{Ga}^{2-}) and singly ionized (V_{Ga}^-) acceptors exist at room temperature in CZ Ga_2O_3 . They observed singly ionized V_{Ga}^- in neutron irradiated β - Ga_2O_3 . The two holes in this acceptor are trapped at individual oxygen ions located on opposite sides of the gallium vacancy. Ga vacancies (V_{Ga}) can exist at tetrahedral (Ga1) and octahedral (Ga2) sites. V_{Ga} forms deep levels at -3 charge state at $E_C-1.62$ and 1.83 eV for V_{Ga1} and V_{Ga2} , respectively, and act as deep acceptors^(28,35). A schematic of the V_{Ga} derived from EPR is shown in Figure 3.

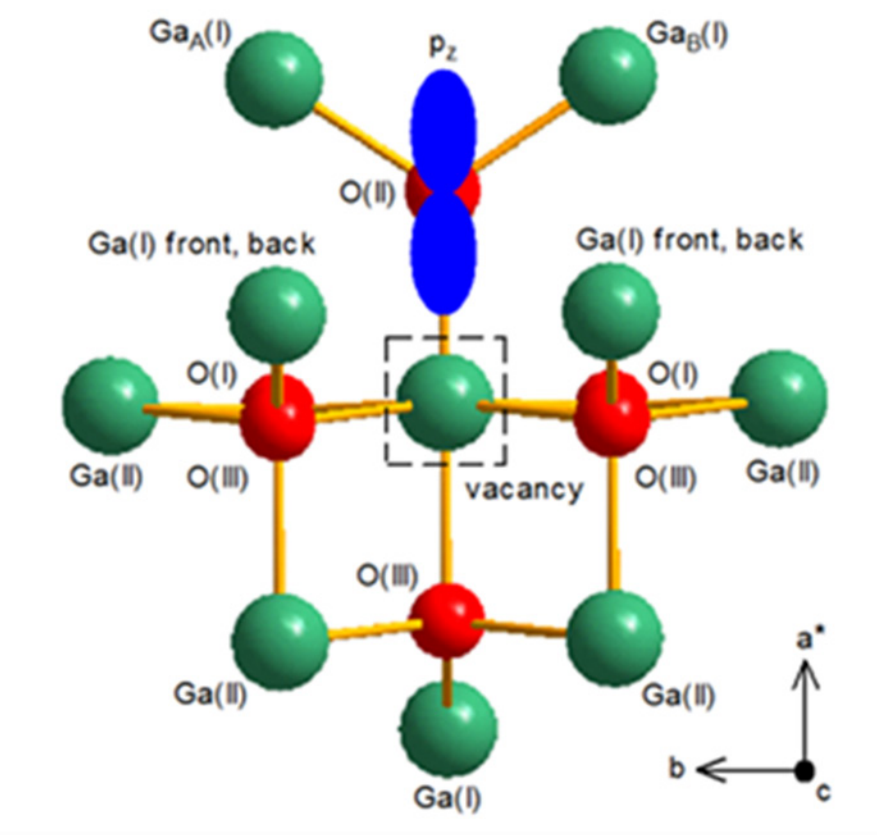


Figure 3. Model of the doubly ionized gallium vacancy in β - Ga_2O_3 . An unpaired spin (the hole) is localized in a p_z orbital on a threefold oxygen ion, O(II), adjacent to a gallium vacancy (dashed square) at a sixfold Ga(II) site⁽³³⁾.

Oxygen vacancies (O_V) cannot explain the observed unintentional n-type conductivity in Ga_2O_3 , since they are deep donors with an ionization energy > 1 eV^(28,38). Theory suggests unintentional impurities are responsible for n-type conductivity, with H, Si, Ge, Sn, F, and Cl all calculated to be shallow donors⁽³⁸⁾. EPR and SIMS identify Si as the primary donor in undoped Ga_2O_3 ⁽³⁵⁾.

5. Summary of Radiation Damage Studies in Ga_2O_3

(i) Proton Damage in Ga_2O_3 Nanobelt Transistors and Rectifiers

10 MeV protons caused a decrease of $>70\%$ in field effect mobility in back-gated field-effect transistors (FETs) fabricated on exfoliated β - Ga_2O_3 nanobelts⁽¹⁹⁾. In addition, there was a positive shift of threshold voltage after proton irradiation at $2 \times 10^{15} \text{ cm}^{-2}$, which corresponds to

approximately 10^5 times the intensity of a solar proton event. Doses of $> 10^{15} \text{ cm}^{-2}$ led to significant suppression of drain current, but the damage could be recovered after annealing at 500°C , similar to that needed for removal of plasma-induced dry etch damage in Ga_2O_3 ⁽²⁷⁾.

In rectifier structures, Ingebrigtsen et al. ⁽⁴⁴⁾ showed that irradiation by 0.6 and 1.9 MeV protons at doses $> 2 \times 10^{13} \text{ cm}^{-2}$ showed complete removal of free charge carriers. Annealing showed a recovery with activation energy of $\sim 1.2 \text{ eV}$. They suggested the charge carrier removal is a result of Fermi-level pinning due to gallium interstitials (Ga_i), vacancies (V_{Ga}), and antisites (Ga_O), while migration and subsequent passivation of V_{Ga} via hydrogen-derived or V_O defects may be responsible for the recovery ⁽⁴⁴⁾.

10 MeV proton irradiation of vertical geometry Ga_2O_3 rectifiers at a fixed fluence of 10^{14} cm^{-2} produced trap states that reduced the carrier concentration with a carrier removal rate of 235.7 cm^{-1} for protons ⁽²⁷⁾. Annealing at 300°C produced a recovery of approximately half of the carriers, while annealing at 450°C almost restored the reverse breakdown voltage. The minority carrier diffusion length decreased from $\sim 340 \text{ nm}$ in the starting material to $\sim 315 \text{ nm}$ after proton irradiation ^(27,41,64). The reverse recovery characteristics showed little change, with values in the range 20-30 nsec before and after proton irradiation.

A compilation of trap states in as-grown and proton-irradiated Ga_2O_3 shows these span a large portion of the gap ^(27,44,45,54,57,62,64-69). Proton irradiation increases the density of E_2^* ($\text{E}_c - 0.75 \text{ eV}$) and $\text{E}_c - 2.3 \text{ eV}$ traps, suggesting these incorporate native defects. Irradiation with 10-20 MeV protons creates deep electron and hole traps, a strong increase in photocapacitance and persistent photocapacitance that partly persists $> 300\text{K}$ ⁽⁶⁴⁾. Typical DLTS spectra from samples before and after 10 MeV proton irradiation are shown in Figure 4. A prominent electron trap near $\text{E}_c - 1.05 \text{ eV}$ is present prior to irradiation. Two minor traps with levels $\text{E}_c - 0.6 \text{ eV}$ and $\text{E}_c - 0.75 \text{ eV}$ are also present. After proton irradiation, the dominant peak in DLTS spectra is an electron trap with level $\text{E}_c - 0.75 \text{ eV}$ with a prominent shoulder due to the $\text{E}_c - 1.05 \text{ eV}$ electron trap-these are respectively E_1 , E_2^* , and E_3 electron traps. The concentrations of E_2^* and E_3 increased and a new trap E_4 at $\text{E}_c - 1.2 \text{ eV}$ emerged after proton irradiation.

Hole traps in the lower half of the bandgap were investigated using optical injection. Three hole-traps H_1 (STH), H_2 (ECB) and H_3 , with activation energies 0.2, 0.4, and 1.3 eV, respectively, were detected ^(27, 64). The Arrhenius plots of these traps are shown in Figure 5. The H_1 (STH) peak corresponds to the transition of polaronic states of self-trapped holes (STH) to mobile holes in the valence band. The H_2 (ECB) feature was assigned to overcoming of the electron capture barrier (ECB) of centers responsible for persistent photocapacitance at $T < 250 \text{ K}$. The H_3 peak was produced by detrapping of holes from $\text{E}_v + (1.3-1.4) \text{ eV}$ hole traps related to V_{Ga} acceptors. A deep acceptor with optical ionization threshold near 2.3 eV is likely responsible for high temperature persistent photocapacitance surviving up to temperatures higher than 400 K.

Other studies prior to irradiation of H^+ ions show at least four levels, labeled E_1 - E_4 , with respective energy levels of 0.56, 0.78, 1.01, and 1.48 eV. The E_2^8 level is the most prominent and may be related to iron ⁽⁴⁴⁾. Figure 6 shows the E_2^8 concentration after irradiation is similar to that before irradiation. There was some instability of the concentrations of the different states observed ⁽⁴⁴⁾.

(ii) Neutron Damage Effects

Farzana et al. ⁽⁴⁵⁾ showed neutron irradiation-induced effects Schottky diodes fabricated on EFG UID (010) substrates produced carrier reduction by irradiation. The primary effect was to increase the concentration of a pre-existing state at $\text{E}_c - 2.00 \text{ eV}$ and introduce a state at $\text{E}_c - 1.29 \text{ eV}$ not observed prior to irradiation. There was a reduction in doping after neutron irradiation, as

shown in Figure 7(a). Carrier removal rates for neutron irradiation are not straightforward because the neutron spectrum has a broad range of energies, unlike monoenergetic electron or proton beams. Thus, the damage cross section is a function of neutron energy ⁽⁴⁶⁾. Using an analysis of neutron flux and damage cross section for a particular neutron energy enables the neutron energy spectrum to be approximated by a mono-energetic equivalent fluence convenient for extraction of carrier removal rate. The carrier removal rate for a 1 MeV equivalent neutron fluence was 51 cm^{-1} (Figure 7(b)). Figure 8 shows the neutron-induced $E_C - 1.03 \text{ eV}$, $E_C - 1.29 \text{ eV}$, and $E_C - 2.00 \text{ eV}$ concentrations, with trap introduction rates of 1.5 cm^{-1} , 8 cm^{-1} , and 9.6 cm^{-1} , respectively ⁽⁴⁵⁾. The sum of the individual introduction rates is lower than the total carrier removal rate of 51 cm^{-1} . The displacement cross-section for Ga_2O_3 irradiated by neutrons, given a displacement threshold energy in Ga_2O_3 , $E_{\text{Ga}}^d = 25 \text{ eV}$, was $\sigma_{\text{Ga}_2\text{O}_3}^{\text{disp}} (1 \text{ MeV}) = 92.3 \text{ MeVmb}$ ^(46,47).

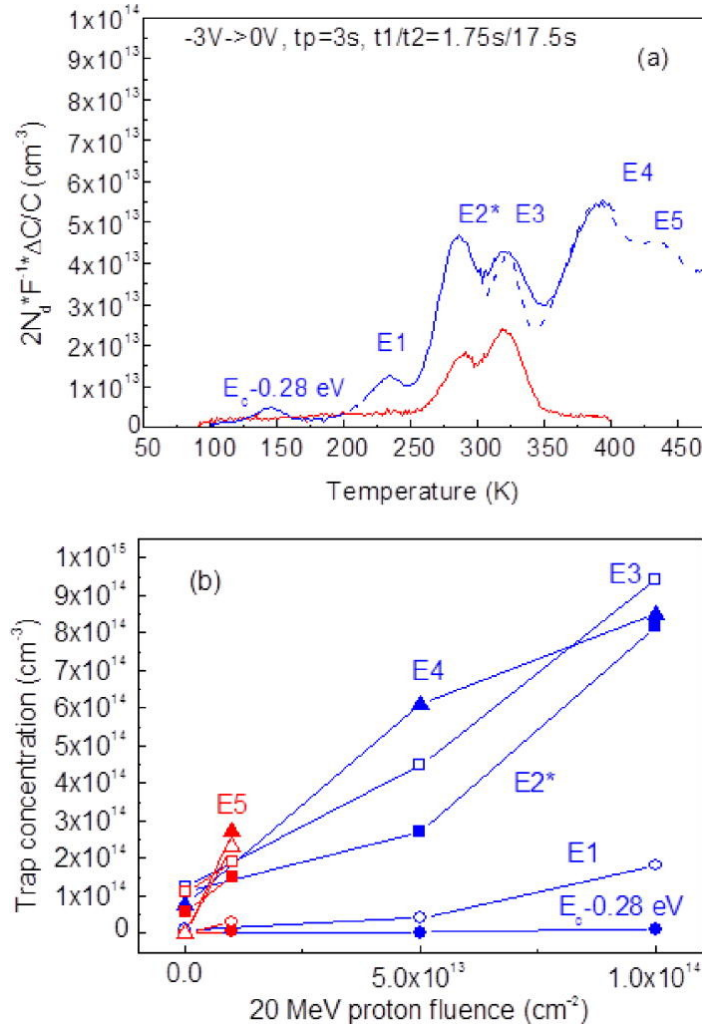


Figure 4. (a) DLTS spectra of $\beta\text{-Ga}_2\text{O}_3$ before (red line) irradiation and after irradiation with 10^{13} cm^{-2} 18 MeV α -particles (b) deep trap concentrations as a function of α -particle (red symbols) or 20 MeV proton (blue symbols) fluence.

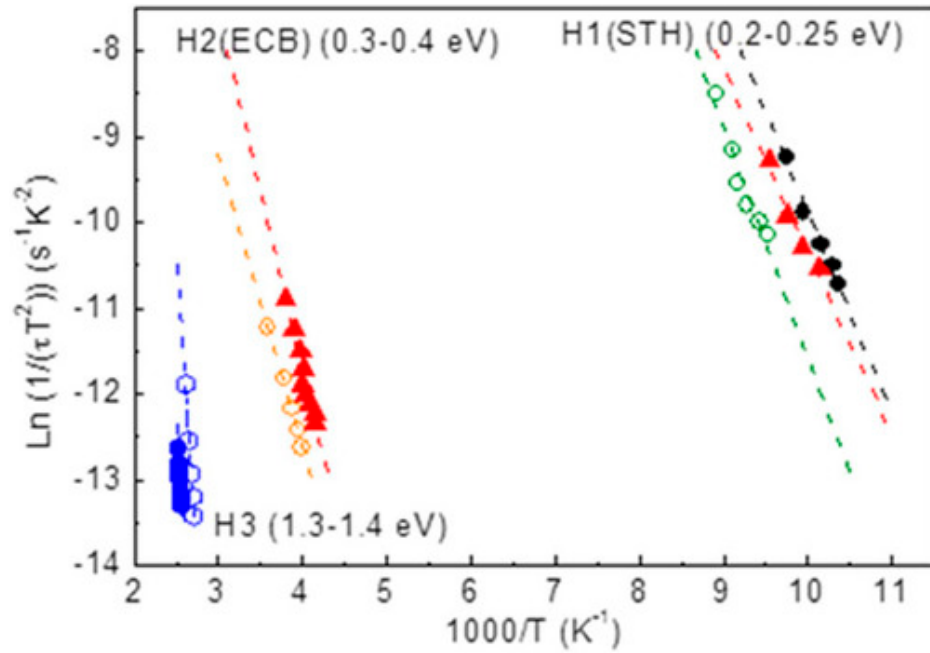


Figure 5. Arrhenius plots for three hole-trap-like signals observed in ODLTS with intrinsic and extrinsic excitation.

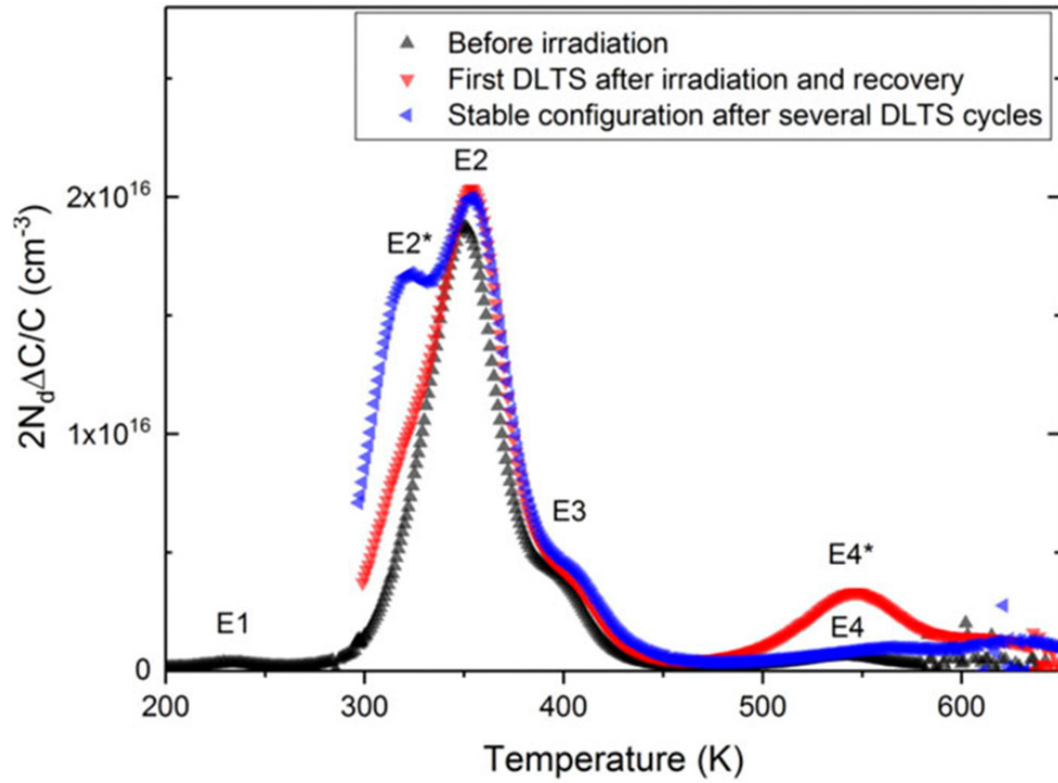


Figure 6. DLTS spectra from Ga₂O₃ before and after irradiation with $6 \times 10^{14} \text{ cm}^{-2} \text{ H}^+$ ions. Two measurements after irradiation are presented to show the difference between the first measurement and that done after stabilization from several cycles ⁽⁴⁴⁾.

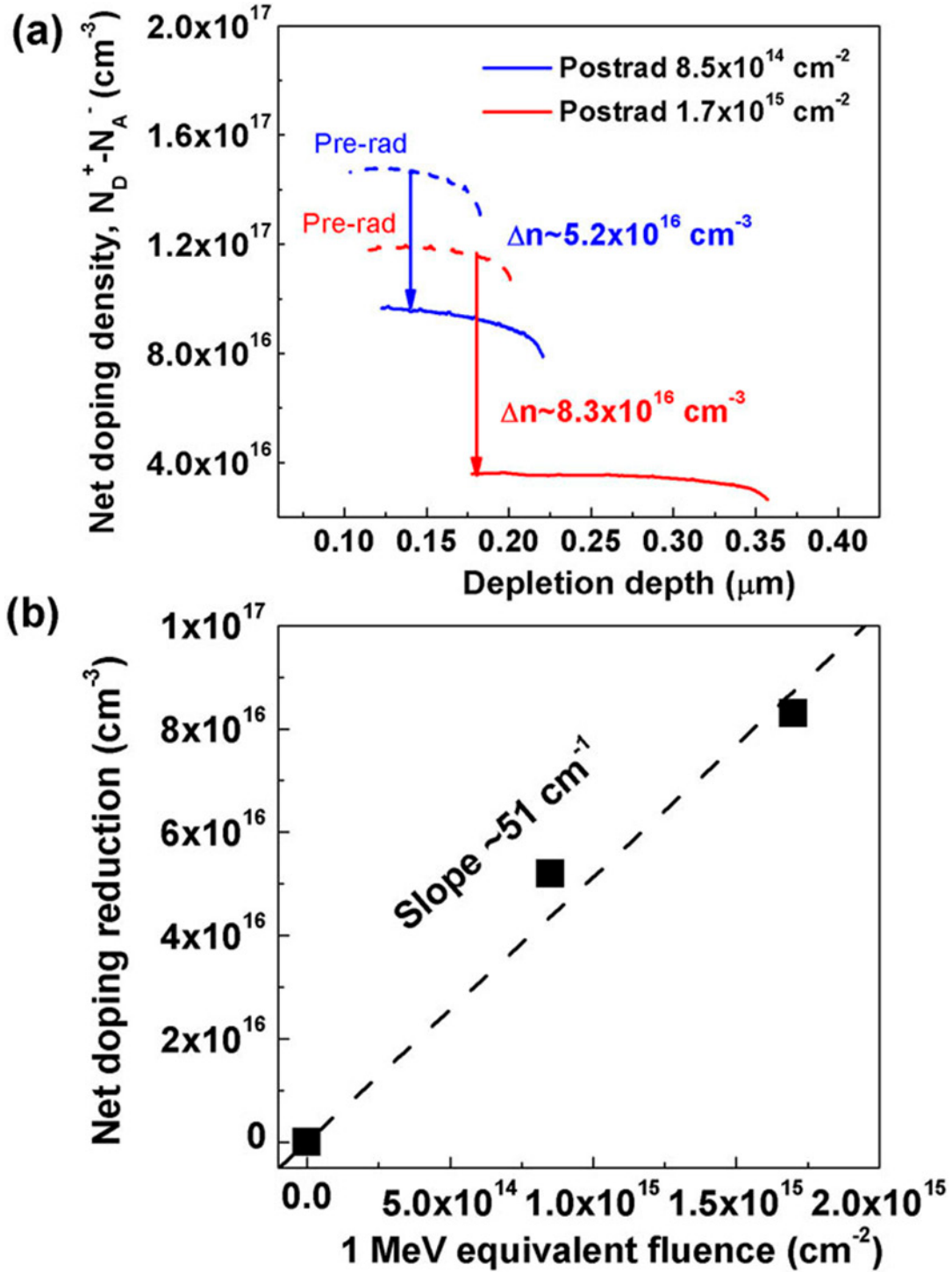


Figure 7. (a) Doping concentration prior to and after neutron irradiation, showing reduction of $\sim 5.2 \times 10^{16}$ cm⁻³ and $\sim 8.3 \times 10^{16}$ cm⁻³ obtained for 1 MeV equivalent fluences of 8.5×10^{14} cm⁻² and 1.7×10^{15} cm⁻², respectively. The dashed lines show the pre-irradiation doping profile for the as-grown samples for the respective cases. (b) Net doping reduction versus 1 MeV equivalent fluences, with carrier removal rate ~ 51 cm⁻¹ (45).

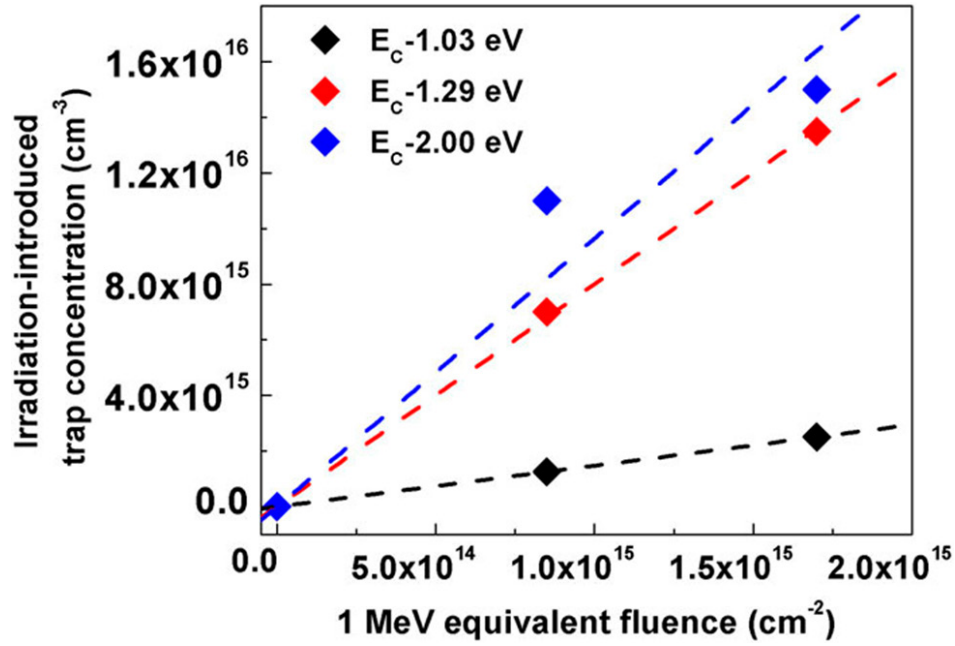


Figure 8. Irradiation-induced trap concentration plotted with respect to the 1 MeV equivalent fluences of $8.5 \times 10^{14} \text{ cm}^{-2}$ and $1.7 \times 10^{15} \text{ cm}^{-2}$ for the $E_c - 1.03 \text{ eV}$, $E_c - 1.29 \text{ eV}$, and $E_c - 2.00 \text{ eV}$ states. The slopes provide the introduction rates as 1.5 cm^{-1} , 8 cm^{-1} , and 9.6 cm^{-1} for $E_c - 1.03 \text{ eV}$, $E_c - 1.29 \text{ eV}$, and $E_c - 2.00 \text{ eV}$, respectively ⁽⁴⁵⁾.

(iii) Alpha Particles

Ga_2O_3 vertical geometry rectifiers subject to 18 MeV alpha particle irradiation at fluences of 10^{12} – 10^{13} cm^{-2} , showed carrier removal rates 406 – 728 cm^{-1} . These are a factor of 2–3 higher than for 10 MeV protons and two orders of magnitude higher than for 1.5 MeV electron irradiation. The on-state resistance of the rectifiers was more degraded by alpha particle irradiation than either ideality factor or barrier height. The reverse breakdown voltage of the rectifiers increased with alpha particle dose as carriers in the drift region were removed by trapping into traps created by the radiation damage, as shown in Figure 9 ^(27,57).

DLTS spectra after irradiation with α -particles showed states at $E_c - 0.28 \text{ eV}$ and $E_c - 1.35 \text{ eV}$. Alpha-particle irradiation increased the concentration of all traps. The main change was $E2^*$ traps whose introduction rate was $\sim 8 \text{ cm}^{-1}$ and $E3$ and $E4$ traps with introduction rate $\sim 20 \text{ cm}^{-1}$. The introduction rates are more than an order of magnitude lower than the carrier removal rates so that, even if all these traps were acceptors, they could not account for the donor decrease after irradiation ^(27,64). The carrier removal rate upon irradiation of $\beta\text{-Ga}_2\text{O}_3$ with α -particles was close to the introduction rate of acceptor Ga_v determined by SRIM modeling. The most dominant deep electron traps detected in irradiated samples in the upper half of the bandgap were the $E2^*$, $E3$, and $E4$ traps with levels from 0.75 – 1.2 eV from the conduction band edge. The electron removal rates for α -radiation were found to be close to the theoretical production rates of vacancies, whereas the concentrations of major electron and hole traps were much lower, suggesting that the main process responsible for carrier removal is the formation of neutral

complexes between vacancies and shallow donors. There was a concurrent decrease in the diffusion length of nonequilibrium charge carriers after irradiation, which correlates with the increase in density of the main electron traps E2* at $E_c - (0.75-0.78)$ eV, E3 at $E_c - (0.95-1.05)$ eV, and E4 at $E_c - 1.2$ eV. The $E_v + 1.4$ eV acceptors could be related to Ga_v acceptors that have not formed complexes with shallow donors but also the Ga_v - acceptor complexes with hydrogen. The levels of electron traps E3 and E4 are close to the two deep oxygen vacancy V_O donors predicted by theory^(28,38), and these could be associated with the lifetime degradation in irradiated β - Ga_2O_3 .

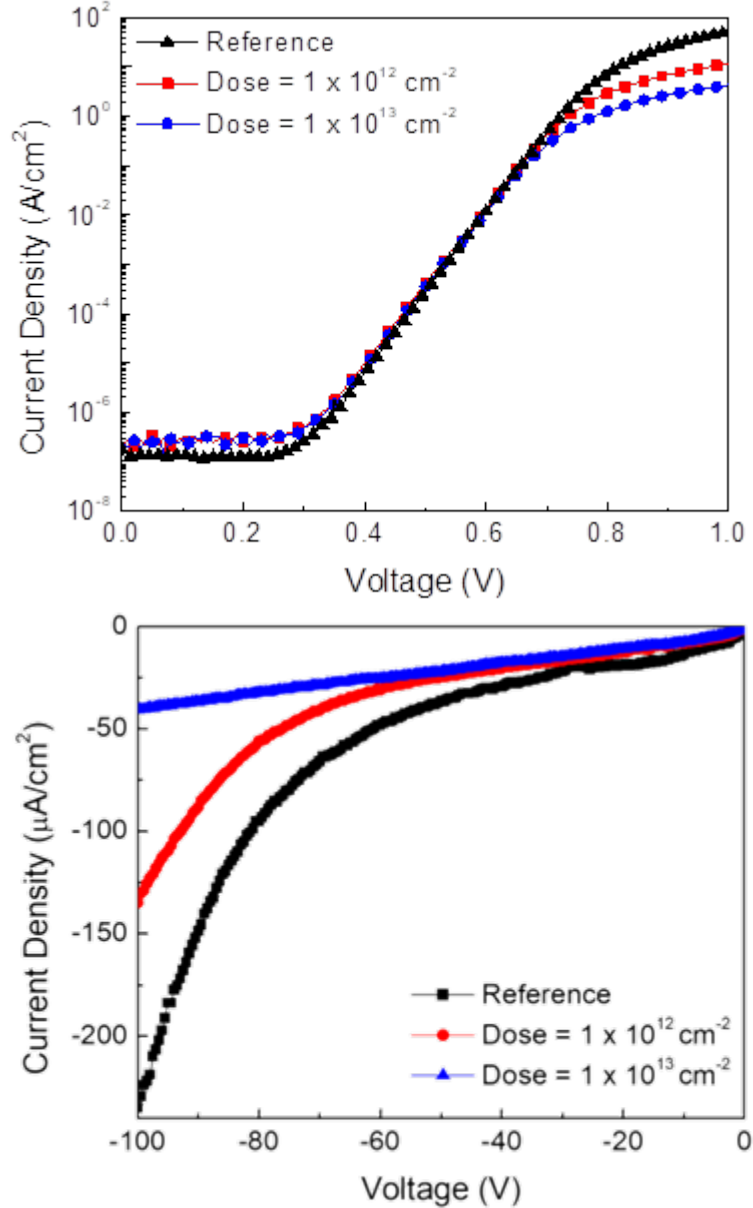


Figure 9. Forward (top) and reverse (bottom) current density–voltage characteristics before and after 18 MeV alpha particle irradiation with fluences of 10^{12} or 10^{13} cm^{-2} (57).

Electron injection on minority carrier transport in β -Ga₂O₃ Schottky rectifiers with 18 MeV alpha particle exposure (fluences of 10^{12} – 10^{13} cm⁻²) was studied from 25-120°C⁽⁶⁵⁾. The diffusion length can be significantly increased by electron injection for both reference and irradiated structures, though the rate of its increase is lower after irradiation (Figure 10). The decrease in activation energy of the electron injection effect on diffusion length for irradiated sample is attributed to radiation-induced generation of additional shallow recombination centers closer to the conduction band edge.

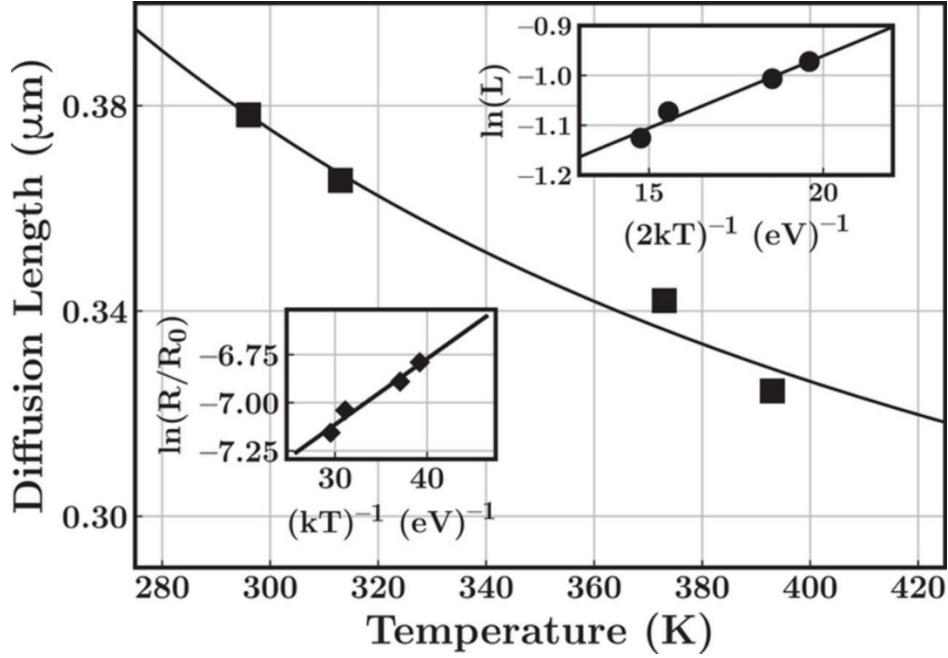


Figure 10. Temperature dependence of diffusion length for α -irradiated Ga₂O₃ rectifier. Inset (top-right): Arrhenius plot, used to calculate activation energy for diffusion length change with temperature. Inset (bottom) Arrhenius plot used to calculate activation energy for diffusion length change due to electron injection⁽⁶⁵⁾.

(iv) Electron Irradiation Damage

1.5 MeV electron irradiation of vertical rectifiers at fluences from 1.79×10^{15} to 1.43×10^{16} cm⁻² caused a reduction in carrier concentration, with carrier removal rate of 4.9 cm⁻¹⁷²⁻⁷⁴. This compares to a carrier removal rate of ~ 300 cm⁻¹ for 10 MeV protons in the same material. The 2 kT region of the forward current-voltage characteristics increased due to electron-induced damage, with a more than 2 order of magnitude increase in on-state resistance at the highest fluence^(27, 54). There was a reduction in reverse current, which scaled with electron fluence. The on/off ratio at -10V reverse bias voltage was severely degraded by electron irradiation. The changes in device characteristics were accompanied by a decrease in electron diffusion length from 325 to 240 μ m at 300 K. Time-resolved cathodoluminescence after 1.5 MeV electron irradiation showed a 210 ps decay lifetime and reduction in carrier lifetime with increased fluence⁽²⁷⁾.

(v) γ -Ray Damage

The effects of gamma ray irradiation on wide bandgap semiconductors are much less pronounced than for proton, electron, or neutron irradiation of these same materials. As an example, in SiC, the effective carrier removal rates normalized to non-ionizing energy loss for gamma rays are up to 6 orders of magnitude less than for alpha particles and approximately two orders of magnitude lower than for electrons and neutrons^(23,58). There was less degradation in Metal Oxide Semiconductor (MOS) transistors than metal-based gate devices, indicating that the gate oxide is a key determinant of the changes due to gamma ray exposure.

The gamma-ray irradiation of lateral depletion mode β -Ga₂O₃ MOSFETs to doses of 1.6 MGray (SiO₂) showed little effect on output current and threshold voltage. Degradation in the gate oxide were found to limit the overall radiation resistance⁽⁶⁶⁾. β -Ga₂O₃ Schottky rectifiers consisting of thick (10 μ m) epitaxial drift regions on conducting substrates also have a high tolerance to ⁶⁰Co gamma ray irradiation, with low carrier removal rate of <1 cm⁻¹ for gamma rays. Changes in diode ideality factor, Schottky barrier height, on-resistance, on-off ratio, and reverse recovery time were all minimal for fluences up to 2×10^{16} cm⁻² (absorbed dose of 100 kGy (Si)). These results are consistent with gamma-irradiation of Ga₂O₃ metal oxide semiconductor field effect transistors (MOSFETs) where changes were ascribed to damage in the gate dielectric and not to the Ga₂O₃ itself. The changes induced by gamma-ray exposure are much smaller than caused by proton, electron, alpha particle and neutron damage in the same rectifier structures.

(vi) X-Ray Damage

Constant voltage stress of β -Ga₂O₃ MOS capacitors with Al₂O₃ gate dielectrics showed increasing electron-trap densities for increasingly positive stress voltages, and hole traps created for irradiation with 10 keV X-rays devices at a dose rate of 31.5 krad (SiO₂) min⁻¹ under grounded bias conditions^(59,60). Stress-induced traps were located primarily in the Al₂O₃ gate dielectric layer and distributed broadly in energy. Oxygen vacancies in the Al₂O₃ were suggested to be most likely defects created. The radiation-induced voltage shifts were comparable to or less than those of the MOSFETs exposed to gamma-rays discussed above

(vii) Dominant Defects Induced by Proton Irradiation

There is interest in the properties of hydrogen because it may be a shallow donor in Ga₂O₃ and therefore contribute to the n-type conductivity, rather than the commonly assumed origin due to native defects such as Ga interstitials or O vacancies, the latter of which are suggested to be deep donors^(28,38-40). There is experimental support that hydrogen may be a shallow donor from muonium and electron paramagnetic resonance (EPR) measurements^(39,40,49).

Qin et al.⁽⁶⁷⁾ showed there can be a high concentration of hydrogen in Ga₂O₃ that is neither electrically or optically active under normal conditions. They suggested that hydrogen shallow donors (possibly H_i and H_O centers predicted by theory)⁽²⁸⁾ are candidates for the reservoirs of “hidden” hydrogen in Ga₂O₃. Hydrogen can trap at any of the O vacancies in the appropriate charge state and the small bond strength of Ga-H species means that the predicted O-H vibrational frequencies would also lie within the free-electron absorption region of the host, and not be visible with IR spectroscopy^(52,53).

EPR spectra from Ga₂O₃ have been interpreted in different ways. Von Bardeleben et al.^(39,68), attributed their result as due to a hole trapped at a Ga(1) vacancy whose structure is identical to the V_{Ga}-2H center found in IR absorption, but with the hydrogens absent and a hole trapped at one of the two dangling O sites. Kananen et al.^(33, 34) attributed the same spectrum to a hole trapped at the Ga(2) vacancy. A second spectrum has been assigned to either a hole trapped at a Ga(2) vacancy, or a self-trapped hole⁽³⁹⁾. Proton irradiation introduces two main paramagnetic defects which are stable at 300K. These were not compatible with undistorted V_{Ga}

on a tetrahedral or an octahedral site (EPR1 center) or a self-trapped hole center (EPR2 center)⁽⁴⁰⁾. A tetrahedral vacancy has a complex $V_{Ga}(\text{tetra})\text{-Ga}_i\text{-}V_{Ga}(\text{tetra})$ configuration, that agrees well with experiment for the EPR1 center⁽³⁸⁾. Figure 11 shows one model consistent with the EPR2 center⁽³⁹⁾. The uncertainty emphasizes that identification of the main defects introduced by irradiation are also still open to interpretation of the origin of the EPR spectra.

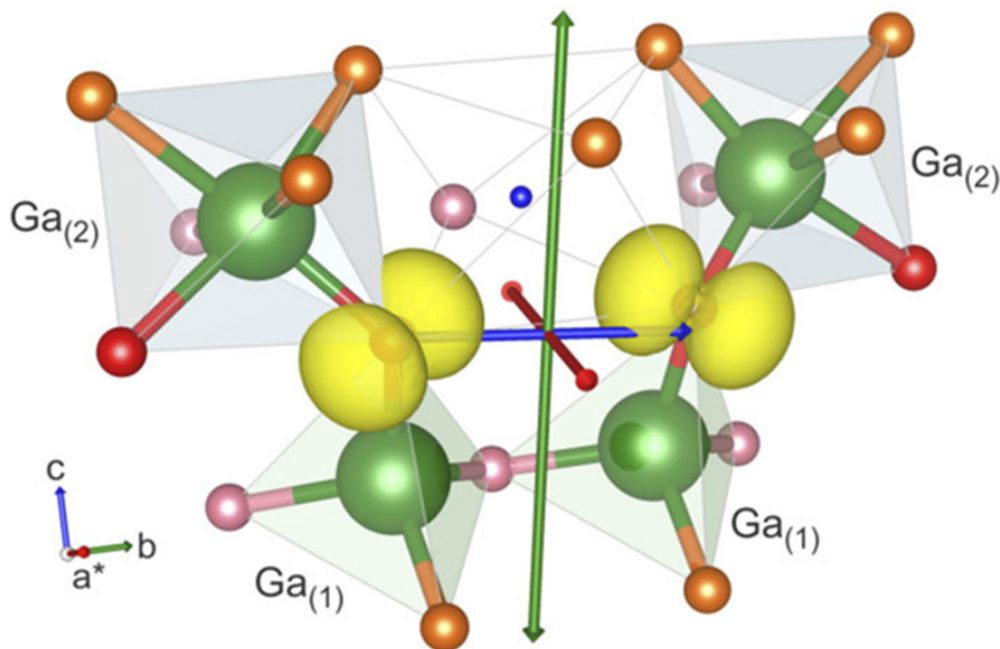


Figure 11. $V_{Ga}^{2-}(\text{octa})$ metastable local structure and spin density (yellow)⁽³⁹⁾.

Data from an IR study by Weiser et al.⁽⁵²⁾ and Qin et al.⁽⁶⁷⁾ on samples implanted with hydrogen or deuterium showed the main defects involve H trapped at a Ga vacancy, the primary member involving a specific two-H configuration. The dominant hydrogen or deuterium absorption lines appear at 3437 and 2545 cm^{-1} , respectively, and were consistent with a model where two H atoms are bonded to a Ga vacancy. When the samples are implanted with hydrogen, additional absorption peaks are observed. As they are annealed, these defects become converted into the 3437 and 2545 cm^{-1} lines at 400 °C. These lines are stable up to 700 °C, where they are then converted into other new lines⁽⁶⁷⁾.

The $V_{Ga(1)}\text{-}2\text{H}$ complex is the dominant O-H center in Ga_2O_3 hydrogenated by annealing in H_2 at elevated temperature ($T > 800^\circ\text{C}$) or by proton implantation^(52,53). This center is thermally stable to 900°C. The spectra shown in Figure 12(a) and (b) for samples containing both H and D reveal that the 3427.1 (2546.4) cm^{-1} center contains two identical, weakly coupled, H (D) atoms. These originate from a structure with two identical H (D) atoms bound to a relaxed $\text{Ga}(1)$ vacancy (Figure 12c)⁽⁶⁷⁾. For samples quenched from 900°C, the $V_{Ga(1)}\text{-}2\text{H}$ complex is absent (Figure 13, spectrum (i)), but additional O-H (O-D) vibrational lines were observed (Figure 13)⁽⁶⁷⁾. A two-step thermal process, involving annealing in H_2 ambient at $> 800^\circ\text{C}$ or greater, followed by cooling to 25°C and then a second anneal at 400°C produced the $V_{Ga(1)}\text{-}2\text{H}$ complex (Figure 13, spectrum (ii)). The interpretation is that there are sources of “hidden” hydrogen that

can be converted into the dominant $V_{\text{Ga}}(1)$ -2H center by thermal annealing at 400°C. Possible assignments for this form of hydrogen include interstitial hydrogen shallow donors, other OH species and H_2 molecules⁽⁶⁷⁾.

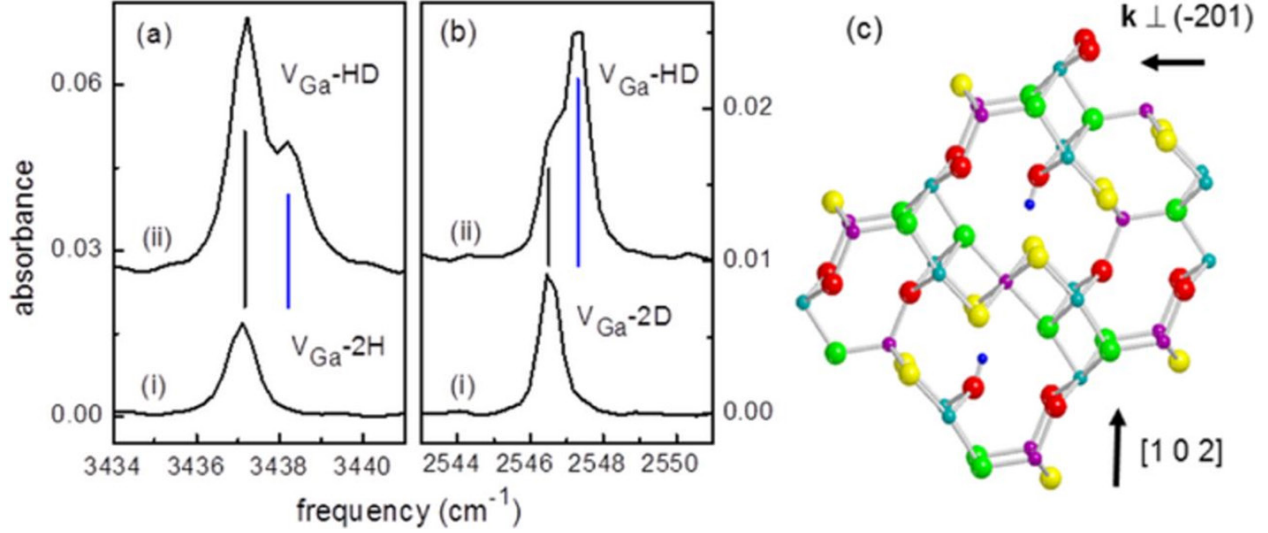


Figure 12. Polarized IR absorption spectra (77 K, resolution 0.5 cm^{-1}) for Ga_2O_3 annealed in H_2 and D_2 ambients. In panel (a), spectrum (i) is the O-H stretching mode for a sample annealed in H_2 . In panel (b), spectrum (i) is the O-D stretching mode for a sample annealed in D_2 . The spectra labeled (ii) in both panels are for a sample annealed in a mixture of H_2 and D_2 . (c) Structure of the $V_{\text{Ga}}(1)$ -2H complex that gives rise to the 3437.0 cm^{-1} IR line⁽⁶⁷⁾.

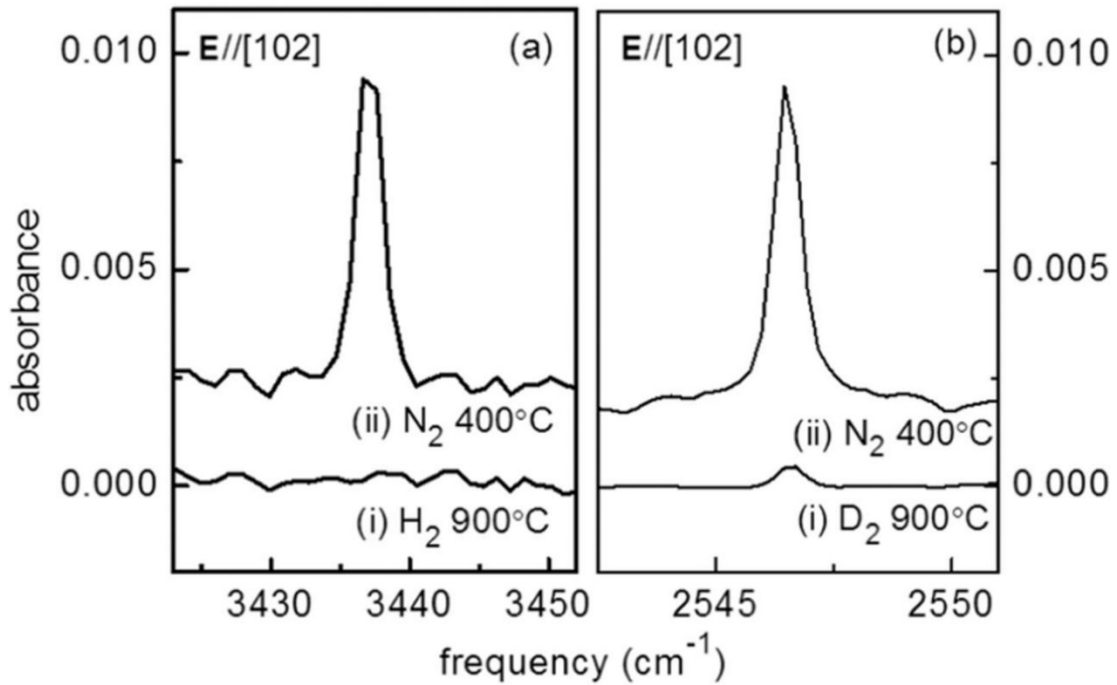


Figure 13 (a) IR absorbance spectra for Ga_2O_3 after two step annealing treatment to introduce hydrogen. Spectrum (i) was measured for a sample annealed initially in an H_2 ambient for 1 h at

900°C. Spectrum (ii) is for the same sample after a subsequent anneal at 400°C in flowing N₂. (b) shows spectra similar to those shown in (a) except with an initial D₂ annealing ambient instead of H₂⁽⁶⁷⁾.

(viii) Annealing of Proton and Alpha Particle Damage in Au-W/ β -Ga₂O₃ Rectifiers

Vertical geometry Ga₂O₃ rectifiers were irradiated with 18 MeV alpha particles to fluences of 1-3x10¹³ cm⁻² or 10 MeV protons to fluences of 1-3x10¹⁴ cm⁻² and then annealed to establish the thermal stability of the radiation damage. The rectifiers employed Au/W rectifying contacts to achieve the requisite thermal stability to allow for annealing studies. The carrier removal rates were ~900 cm⁻¹ for the α -particles and ~200 for the protons. Annealing at 500°C was found to restore the carrier concentration in the α -particle irradiated devices, while 450°C annealing brought substantial recovery of the proton irradiated devices. This is a similar temperature range as established for annealing of plasma-induced damage in Ga₂O₃, suggesting a common origin of point defects, predominantly Ga vacancies and their complexes. The reverse breakdown voltages and diode on/off ratios are also significantly recovered by annealing after irradiation. The carrier removal rate N_R was calculated from the change in sheet carrier density as a result of irradiation with fluence Φ , according to

$$N_R = \frac{n_{s0} - n_s}{\Phi}$$

Table I summarizes the effect of both types of radiation exposure on the Schottky barrier height, diode ideality factor and on-state resistance for the as-irradiated and annealed conditions.

Table 1. Summary of barrier heights, ideality factors and on-state resistances.

Irradiation Dose	Sample	Schottky Barrier Height (eV)	Ideality Factor (-)	On Resistance (m Ω *cm ²)
Reference	Reference	0.77	1.15	4.9
Alpha 10 ¹³	Irradiated	0.68	1.23	17.8
	450 °C 5 min anneal	0.7	1.2	6.3
	400 °C 5 min anneal	0.65	1.29	6.3
	Thinned down	0.74	1.12	745
Alpha 3x10 ¹³	Irradiated	0.66	1.28	19.0
	450 °C 5 min anneal	0.79	1.12	8.6
	500 °C 5 min anneal	0.79	1.12	6.9
Proton 10 ¹⁴	Irradiated	0.74	1.12	16.9
	450 °C 5 min anneal	0.76	1.09	6.4

Proton 3×10^{14}	Irradiated	0.74	1.13	13.1
	450 °C 5 min anneal	0.82	1.09	7

(ix) Pulsed Fast Reactor Neutron Irradiation Effects in Si doped n-type β -Ga₂O₃

The effects of pulsed neutron irradiation on Si doped n-type β -Ga₂O₃ films grown by halide vapor phase epitaxy (HVPE) on bulk Sn doped n⁺ β -Ga₂O₃ substrates are reported. This irradiation leads to an almost linear increase with neutron fluence of the density of deep electron traps E2* (E_c-0.74 eV), E3 (E_c-1.05 eV), and E4 (E_c-1.2 eV), with an introduction rate close to 0.4-0.6 cm⁻¹ while the density of the E2 traps (E_c-0.8 eV) related to Fe was virtually unchanged. In addition, the increase in the density of deep traps with optical ionization threshold of 1.3 eV, 2.3 eV, and 3.1 eV with an introduction rate close to 0.8-2 cm⁻¹ was observed. The carrier removal rate under our conditions was 28 cm⁻¹. Neutron irradiation also led to a measurable decrease of the diffusion length of nonequilibrium charge carriers. The results are qualitatively similar to previous reports for proton and α -particle irradiation of HVPE β -Ga₂O₃. When comparing the findings with those described earlier for bulk neutron irradiated Ga₂O₃, we observe lower starting densities of electron and hole traps and lower introduction rates for these traps in the epitaxial structures. The carrier removal rates were comparable to those in bulk crystals.

(x) Effect of Electron Injection on Minority Carrier Transport in 10 MeV Proton Irradiated β -Ga₂O₃ Schottky Rectifiers

The effect of extended duration electron beam exposure on the minority carrier transport properties of 10 MeV proton irradiated (fluence $\sim 10^{14}$ cm⁻²) Si-doped β -Ga₂O₃ Schottky rectifiers was examined. The diffusion length (L) of minority carriers is found to decrease with temperature from 330 nm at 21 °C to 289 nm at 120 °C, with an activation energy of ~ 26 meV. This energy corresponds to the presence of shallow Si trap-levels. Extended duration electron beam exposure enhances L from 330 nm to 726 nm at room temperature. The rate of increase for L is lower with increased temperature, with an activation energy of 43 meV. Proton irradiation was performed by a 10 MeV proton beam generated by a MC-50 cyclotron at Korea Institute of Radiological and Medical Science with a beam fluence of 10^{14} cm⁻². The range of protons in the material was found to be 330 μ m, completely irradiating the epilayer and a large portion of the substrate. Figure 13 shows a schematic diagram showing the structure of the Schottky rectifiers used in this study. The temperature dependent activation energy for change in L was found to be 26 meV and is attributed to shallow Si trap levels. The activation energy for temperature dependence of electron injection effect was calculated as 43 meV. Finally, the effect of proton irradiation was compared to alpha-particle irradiation and a control reference structure. The effect of electron injection in both types of radiation damage was found to be similar in nature with comparable activation energies for temperature dependence of L and the electron injection effect.

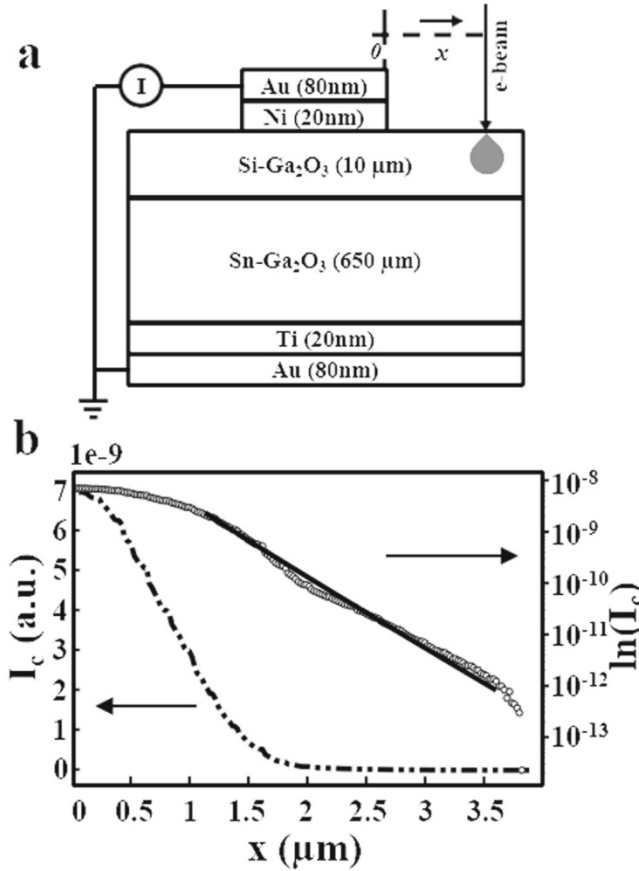


Figure 14. (a) Schematic of the Si-doped β -Ga₂O₃ Schottky rectifiers used in this study. EBIC line-scan is performed by scanning the electron beam laterally across the Schottky barrier. (b) EBIC line-scan raw data (left) and $\ln(I)$ vs x fitted with $\exp(-x/L)/x^\alpha$ to extract L (right).

(xi) Simulation of Radiation Damage, Hydrogen and Fluorine Effects

Deuterium was incorporated into single crystal, bulk Ga₂O₃ via ion implantation or plasma exposure, and subsequent annealing at different temperatures was done to observe the diffusion profile of the deuterium. The thermal stability of deuterium in both the deuterium incorporation techniques was been examined, as deuterium moves through the bulk material to be outgased at the surface after annealing. The mechanisms of this outdiffusion kinetics have been incorporated into the FLOOPS simulator. The ion-implantation creates a lot of point defects/traps in the material which turn causes the deuterium to be trapped at these sites, and released after the annealing. A complex model consisting of the deuterium diffusion (via Fick's law), with vacancy and interstitial diffusion, trapping and de-trapping, and a surface outgas rate is used. However, the plasma exposure does not create traps in the bulk, but the outdiffusion model has deuterium diffusion which is dominated by the formation of deuterium molecules. In conclusion, very good fits to the SIMS profile have been achieved via this simulation model, furthermore, this helps in obtaining the migration energetics and various activation energies.

A similar simulation model has been formulated to study plasma incorporated fluorine in Ga₂O₃. Rectifiers made on epitaxial layers on bulk substrates have been exposed to a CF₄ plasma

followed by subsequent annealing at various temperatures, and we observe a similar mechanism where the fluorine molecule formation is dominant. The experimental SIMS data is accurately fit by this model which helps in extracting the activation energies.

Nickel - β -Ga₂O₃ Schottky diodes have been irradiated with electrons and protons with before and after radiation IV measurements performed. The goal of this study is to simulate the IV curve via the radiation damage, mobility variations, SBH change and variations in the carrier concentration. In modelling the IV we use the FLOODS TCAD as the PDE (partial differential equation) solver. The basic device equations plus other complex defect/trap related equations have been incorporated into the script. In the electron irradiation case, through TRIM calculations and other studies we've concluded an increase in the gallium vacancies which act as compensation for the n-type doping, which eventually reduces the conductivity. For the proton irradiation case, certain DLTS, DLOS and EPR measurements suggest the introduction of a new gallium vacancy-hydrogen complex which is an acceptor trap, hence reducing the carrier concentration. The increase in concentration of these extra traps (gallium and oxygen vacancies/vacancy complexes) also reduce the carrier mobility as it increases impurity scattering. The donor traps observed in the forbidden gap have no effect on the device performance at low forward bias as they are below the fermi level, and hence do not get ionized, however the acceptor traps are all well below the fermi level and hence are occupied, i.e. ionized and cause the compensation. A trap assisted tunneling model is currently being studied to simulate the 0-0.5V sections of the IV curves, whereas further research on the mechanism of the change in SBH is required.

Conclusions

The initial data on proton, electron, x-ray, gamma and neutron irradiation of β -Ga₂O₃ show fairly comparable radiation resistance to GaN under similar conditions. Figure 15 shows a compilation of carrier removal rates in Ga₂O₃ for different types and energy of radiation. The carrier removal rates in irradiated rectifier structures range from $\sim 5 \text{ cm}^{-1}$ for 1.5 MeV electrons to 730 cm^{-1} for 18 MeV alpha particles. Thermal annealing at $\sim 500^\circ\text{C}$ brings a significant recovery towards the initial, un-irradiated characteristics. The dominant defect formed in Ga₂O₃ by annealing in an H₂ ambient or by the implantation of protons is a specific relaxed V_{Ga}-2H structure for the 3437 cm^{-1} line that dominates the infrared absorption spectra. There is significant scope for additional work to determine carrier removal rates at additional energies for each radiation type, to look for dose-rate effects, SEU responses, the role of interfaces in MOS structures and annealing stages of the induced defects. In the latter case, it is of importance to know whether in-situ thermal annealing or forward biased minority carrier injection annealing are effective in Ga₂O₃ devices, since these could be used as simple refresh cycles for radiation damaged devices.

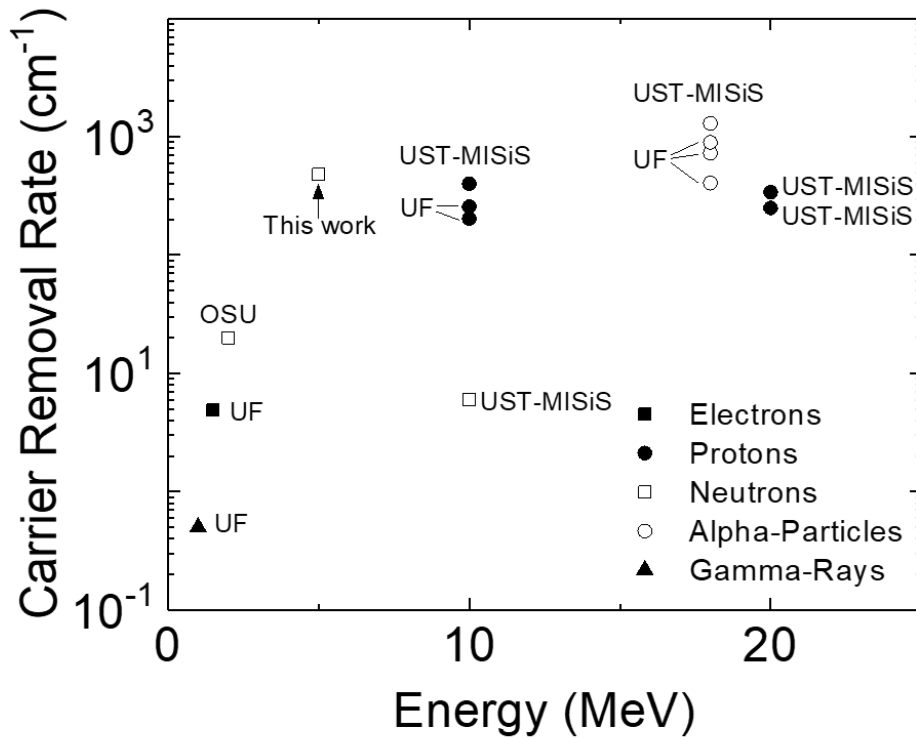


Figure 15. Carrier removal rate in Ga_2O_3 as a function of energy for different types of radiation. Data is either from University of Florida (UF) ^(27,54, 57, 66), National University of Science and Technology (UST-MISiS) ^(41, 64, 69) or Ohio State University (OSU) ⁽⁴⁵⁾.

Our main conclusions are:

- The carrier removal rate decreases in the sequence alpha particles, protons, electrons neutrons and gamma rays in vertical geometry rectifiers
- Defects created by irradiation introduce scattering centers which result in degraded mobility and resulting in reduced carrier density. These two effects are responsible for degraded I-V behavior, including reduced current and, increased ON-resistance in rectifier structures.
- The thermal stability of radiation damage in Ga_2O_3 vertical rectifiers was established for alpha and proton-irradiation. The I-V, C-V and on/off ratios are all significantly degraded by moderate fluences of these forms of radiation, but can be essentially recovered by annealing at 450 °C for 5 mins. Other parameters such as Schottky barrier height, ideality factor and reverse recovery characteristics are less affected by radiation damage.
- The commonality of annealing stages between these ionizing forms of radiation and plasma -induced damage in Ga_2O_3 suggest a common origin of point defects. In the vertical geometry devices studied here, the damage created in the drift region is most

important in determining the relative degradation of device performance, as evidenced by our experiments where we removed the end-of-range damage in the substrate.

- There was no effect of hydrogen introduction in the semiconductor on the degradation of Ga₂O₃ rectifiers as a result of proton damage nor any effect of electric field on the degree of damage introduction.
- FLOODS simulator provides a powerful tool for modeling and understanding radiation effects in nitride heterostructures.

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What opportunities for training and professional development has the project provided?

All the students involved presented their work at international conferences and took a variety of training courses.

Two of the students involved in the projects gave oral presentations on their work at the AVS Florida Chapter annual conference in Orlando, FL in March.2017

Two of the students involved in the projects gave oral presentations on their work at the 64th AVS International Symposium and Exhibition in Tampa in October 2017.

One of the students gave 2 presentations at the 233rd ECS Meeting, Seattle, WA, May 2018.

Two of the students gave presentations at the APS March Meeting, Los Angeles, CA, March 2018.

Two of the students involved in the project gave oral presentations on their work at the 65th AVS International Symposium and Exhibition in Long Beach in October 2018.

Two of the students gave presentations at the 235th ECS Meeting, Dallas, TX, May 2019.

One of the students gave a presentation at the Gallium Oxide workshop in Columbus, OH, August 2019.

One of the students gave a presentation at the 76th DRC conference, Santa Barbara, CA, June 2019.

The graduate students, undergrads or post-docs supported, their major or subject area, and expected MS or PhD dates are as follows:

Jiancheng Yang, Chem Eng, Ph. D, April 2019 (Keysight)
 Ribhu Sharma, MSE, PhD, exp May 2020
 Chaker Fares, Chem Eng, exp. May 2020 (Northrop-Grumman)
 Patrick Carey, Chem. Eng., Ph. D exp. Aug 2020
 Shihyun Ahn, Chem. Eng. PhD Dec 2017 (TSC)
 Erin Patrick, Post-Doc (Assistant Prof. UF)
 Kimberly Beers, undergrad, BS Dec 2019 (grad school)

Randy Elhassani, undergrad, BS Dec 2019 (grad school)
Jessica Partain, undergrad, BS exp. May 2020 (grad school)

How have the results been disseminated to communities of interest?

We have published 84 refereed journal publications in archival journals over the length of the contract, as well as 4 book chapters and 52 conference presentations.

Publications

“Thermal Stability of Implanted or Plasma Exposed Deuterium in Single Crystal Ga₂O₃”, S. Ahn, F. Ren, Erin Patrick, Mark E. Law, and S. J. Pearton, ECS J. Solid State Sci. Technol., 6, Q3026 (2017). <http://doi:10.1149/2.0051702jss>

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We published 97 papers in peer-reviewed journals, as per the list earlier in the report and gave a total of 52 conference presentations, including 7 invited, including the following conferences:

64th AVS International Symposium and Exhibition in Tampa in October 2017.

SPIE West, San Francisco, CA, January 2018.

Government Microcircuit Applications and Critical Technology Conference (GOMACTech) 2018, Miami, FL, March 2018.

APS March Meeting, Los Angeles, CA, March 2018.

International Conference on Metallurgical Coatings and Thin Films, San Diego. May 2018.
233rd ECS Meeting, Seattle, WA, May 2018.

65th AVS International Symposium and Exhibition in Long Beach, CA in October 2018.

SPIE West, San Francisco, CA, January 2019.

Government Microcircuit Applications and Critical Technology Conference (GOMACTech)
2019, Albuquerque, NM, March 2019.

European MRS, Warsaw, Poland, September 2018.

WODIM 2018-20th Workshop on Dielectrics in Microelectronics Conference, Berlin, June 2018.

Fall MRS, Boston, MA, December 2018.

235th ECS Meeting, Dallas, TX, May 2019.

BIAMS 2018, 14th Int. Conf. Beam Injection Assessment of Microstructures in Semiconductors,
Seoul, Korea, June 18-21, 2019

76th Device Research Conference, Santa Barbara, CA, June 2019

2018 US Workshop on Gallium Oxide, Columbus, OH, August 2019.

Gordon Research Conference, Insight, Characterization and Control of Defects in Advanced
Materials, Colby College, NH, August, 2019.

ECS meeting, Atlanta, GA, October 2019

AiChE annual meeting, Orlando, FL, November 2019

SPIE Meeting, Photonics West, Feb 2020.

The details of the object-oriented codes developed are at the url:

http://www.flooxs.ece.ufl.edu/index.php/Main_Page#DTRA_Contract_Ga2O3_Radiation_Effects

The core software, commercialized by ISE / Synopsis as Sentaurus -This process simulator is based on FLOOPS, which is licensed at over 350 sites world-wide (FLOOPS is a C++ based simulation program that uses physical models to describe process steps such as implantation, oxidation, and diffusion. It uses the Alagator scripting language to define partial differential equations (pde's) and boundary conditions for use with the diffusion command and device simulation [floops manual].It makes use of 'operators', which are functions with values to specify in partial differential equations. The five current operators are: ddt which takes time derivatives, grad which takes spatial derivatives, sgrad which takes spatial derivatives for device

simulation, and diff and trans operators which takes the derivative of the arguments parallel and perpendicular to the edge of evaluation used in the device simulator.

The manual for the software is available at

http://www.flooxs.ece.ufl.edu/index.php/Main_Page#Manual