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10 MeV proton damage in $\beta$-Ga$_2$O$_3$ Schottky rectifiers

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The electrical performance of vertical geometry Ga$_2$O$_3$ rectifiers was measured before and after 10 MeV proton irradiation at a fixed fluence of $10^{14}$ cm$^{-2}$, as well as subsequent annealing up to 450$^\circ$C. Point defects introduced by the proton damage create trap states that reduce the carrier concentration in the Ga$_2$O$_3$, with a carrier removal rate of 235.7 cm$^{-1}$ for protons of this energy. The carrier removal rates under these conditions are comparable to GaN-based films and heterostructures. Even annealing at 300$^\circ$C produces a recovery of approximately half of the carriers in the Ga$_2$O$_3$, while annealing at 450$^\circ$C almost restores the reverse breakdown voltage. The on/off ratio of the rectifiers was severely degraded by proton damage and this was only partially recovered by 450$^\circ$C annealing. The minority carrier diffusion length decreased from $\sim$340 nm in the starting material to $\sim$315 nm after the proton irradiation. The reverse recovery characteristics showed little change with values in the range 20–30 ns before and after proton irradiation. Published by the AVS. https://doi.org/10.1116/1.5013155

I. INTRODUCTION

$\beta$-Ga$_2$O$_3$ is attracting interest for power electronics and solar blind photodetectors because of its large bandgap ($\sim$4.9 eV) and critical electric field ($E_C$) strength of 8 MV cm$^{-1}$ and the ready availability of high quality, large area wafers. There is always interest in the ability of wide bandgap semiconductors to withstand high radiation fluences of the type encountered in satellite or other space-borne applications.\textsuperscript{19} Given its high bond strength and expected high vacancy formation energy, $\beta$-Ga$_2$O$_3$ is likely to be very radiation hard based on the reduced density of atomic displacements expected for a given energy of nonionizing radiation exposure. In general, the bond energies scale with bandgap, meaning, for example, that a material like GaN with a bandgap of 3.4 eV is likely to be more radiation hard than GaAs with a bandgap of 1.43 eV.\textsuperscript{20}–\textsuperscript{30} However, it has been pointed out by Weaver et al.\textsuperscript{20} that while fewer defects are created in GaN than in GaAs because of the larger values of $E_d$, the difference (36%) is insufficient to explain the order-of-magnitude (1000%) difference in radiation tolerance. They suggested that creation of Ga vacancies, which are triple acceptors, causes the number of acceptors to significantly increase and ($N_D$-$N_a$) to decrease.\textsuperscript{20} It is not yet clear whether a similar explanation can be applied to other wide bandgap materials, or this is specific to the case of GaN. Korhonen et al.\textsuperscript{37} investigated the electrical compensation in n-type Ga$_2$O$_3$ by Ga vacancies in Ga$_2$O$_3$ thin films using positron annihilation spectroscopy. They estimated a $V_{Ga}$ concentration of at least $5 \times 10^{18}$ cm$^{-3}$ in their undoped and Si-doped samples.\textsuperscript{37} Since theoretical calculations predict that these $V_{Ga}$ should be in a negative charge state for n-type samples,\textsuperscript{3,5} they will compensate the n-type doping. Kananen et al.\textsuperscript{38} used EPR to demonstrate the presence of both doubly ionized ($V_{Ga}^{2+}$) and singly ionized ($V_{Ga}^+$) acceptors at room temperature in Czochralski Ga$_2$O$_3$.

There are three principal sources of space radiation, namely, from cosmic rays, trapped radiation in the Earth’s radiation belts, and finally, solar particle events.\textsuperscript{19} The cosmic rays consist predominantly of protons, the radiation belts contain energetic protons and electrons, while solar particle events are mostly lower energy protons and electrons, in which the typical integral proton fluxes at 10 MeV are of order $10^{14}$ cm$^{-2}$.\textsuperscript{19} Thus, it is important to understand the effect of energetic proton irradiation on Ga$_2$O$_3$.

There are now some initial reports of the effect of proton, electron, gamma ray and neutron irradiation of n-type $\beta$-Ga$_2$O$_3$ rectifiers and UV photodetectors under conditions relevant to low earth orbit of satellites containing these types of devices.\textsuperscript{23–27} The carrier removal rates for proton, electron and neutron irradiation are found to be comparable to those in GaN of similar doping levels for the same types of fluences.\textsuperscript{23–27} The main defect created in Ga$_2$O$_3$ by proton irradiation has been identified as a Ga vacancy with two hydrogens attached.\textsuperscript{39} Neutron irradiation produces a dominant state with an ionization level near $E_C - 1.88$ eV.\textsuperscript{26}

In this paper, we discuss the effect of 10 MeV proton irradiation on vertical $\beta$-Ga$_2$O$_3$ Schottky rectifiers, which provide a convenient platform for monitoring changes in the properties of Ga$_2$O$_3$ subject to radiation fluences. The carrier removal rate is found to be $\sim$236 cm$^{-1}$ for this proton...
energy. The results are contrasted with the behavior of GaN subjected to similar exposures.

II. EXPERIMENT

The starting samples were bulk \( \beta \)-phase \( \text{Ga}_2\text{O}_3 \) single crystal wafers (~650 \( \mu \)m thick) with (001) surface orientation grown by the edge-defined film-fed growth method.\(^1\) Hall measurements showed the Sn-doped samples had carrier concentration of \( 2.2 \times 10^{18} \text{ cm}^{-3} \). Epitaxial layers (initially \( \sim 20 \mu \text{m} \) thick) of lightly Si-doped n-type \( \text{Ga}_2\text{O}_3 \) \( (\sim 3 \times 10^{16} \text{ cm}^{-3}) \) were grown on these substrates by hydride vapor phase epitaxy. After growth, the episphere was subjected to chemical mechanical polishing to planarize the surface, with a final thickness of \( \sim 10 \mu \text{m} \).

Diodes were fabricated by depositing a full area back Ohmic contacts of Ti/Au (20 nm/80 nm) by e-beam evaporation. The front sides were patterned by lift-off of electron-beam deposited Schottky contacts Ni/Au (20 nm/80 nm) with 210 \( \mu \text{m} \). Figure 1 shows a schematic of the rectifier layer structure. Current–voltage (I-V) characteristics were recorded at 25°C on an Agilent 4145B parameter analyzer or a Tektronix 370A curve tracer. The 10-MeV proton beam was generated using a MC-50 Cyclotron at the Korea Institute of Radiological and Medical Science. The proton beam was injected into a low-vacuum chamber, where the \( \beta \)-\( \text{Ga}_2\text{O}_3 \)-based devices were loaded, facing the proton beam. The average beam-current, measured by Faraday-cup, was 100 nA during proton irradiation process. Proton fluence was fixed at 100 \( \mu \text{A/cm}^2 \). Samples were annealed in flowing \( \text{N}_2 \) ambient in a surface science integration rapid thermal program and is 330°C.

III. RESULTS AND DISCUSSION

The reverse bias I-V characteristics shown in Fig. 2 demonstrate that the proton irradiation caused a significant increase in breakdown voltage. This is a result of carrier removal in the epilayer by nonionizing energy loss that creates electron traps and acceptor states that compensate the initial donor doping. Yang et al.\(^{27}\) reported a decrease in both channel conductivity and mobility in proton irradiated \( \beta \)-\( \text{Ga}_2\text{O}_3 \) nanobelt field effect transistors. The latter occurs because of the more significant Coulombic carrier scattering as charged defects are created by the proton energy loss during their stopping process. Note that postirradiation annealing produced a partial recovery of the I-V characteristics. This is consistent with the behavior reported earlier for dry etch-induced damage to the near-surface of \( \text{Ga}_2\text{O}_3 \), where annealing at 450°C was found to essentially restore the values of barrier height and ideality factor of plasma damaged diodes.\(^{28}\)

The recovery in electrical properties is also reflected in the 1/C\(^2\)-V plots for the rectifiers after proton irradiation and subsequent annealing shown in Fig. 3. The calculated carrier removal rate was 235.7 cm\(^{-1}\) for the 10 MeV protons. The initial carrier density of 3.1 \( \times 10^{16} \text{ cm}^{-3} \) was reduced to 8.03 \( \times 10^{15} \text{ cm}^{-3} \) after proton irradiation and annealing at 300°C restored this approximately half-way, to 1.25 \( \times 10^{10} \text{ cm}^{-3} \). This compares with a carrier removal rate of \( \sim 4.9 \text{ cm}^{-1} \) for 1.5 MeV electron irradiation of the same type of rectifiers.\(^{25}\)

Thus, the protons are roughly 50 times more damaging than the electrons.

Figure 4 shows the rectifier on/off ratio when switching from +1 V forward bias to the reverse voltages shown on the x-axis. The unirradiated rectifiers showed on/off ratios of \( > 1 \times 10^5 \) across the entire voltage range investigated. This is severely degraded by proton irradiation, to values in the range 10\(^2\)–10\(^3\). This is due to the reduction of forward current as the carrier density is reduced by the proton damage-induced trap introduction. Annealing at 300°C did not have a significant recovery effect, while annealing at 450°C restored the on/off ratios to \( \sim 1 \times 10^4 \). These results show how the operating characteristics of the rectifiers are degraded by exposure to high energy proton fluences.

Figure 5 shows a compilation of reported carrier removal rates for GaN-based heterostructures (AlGaN/GaN and InAlN/GaN high electron mobility transistor structures)\(^{21,22}\) along with single layers of n- or p-GaN as a function of radiation type and energy. Note that protons exhibit the highest

![Fig. 1](image1.png)

![Fig. 2](image2.png)
carrier removal rates of the four types of radiation represented. We have plotted the results obtained here for proton irradiation of Ga$_2$O$_3$, as well as previously reported values for electron$^{25}$ and neutron irradiation.$^{26}$ The results for Ga$_2$O$_3$ are generally comparable to those for GaN and indicate that the former is a good candidate for space-borne applications.

The EBIC technique was used to determine minority carrier diffusion length as a function of temperature for each irradiation dose.$^{40,41}$ Figure 6 (top) shows a wire-bonded rectifier packaged for this measurement. As shown in Fig. 6 (bottom), the room temperature value of $L$ was $\sim$340 nm for the nonirradiated sample and decreased with increasing temperature due to increased scattering or recombination. After proton irradiation, the room temperature diffusion length was reduced to $\sim$315 nm. The diffusion length depends exponentially on temperature through an Arrhenius factor. The values of the activation energy were 41.8 and 16.2 meV for the nonirradiated and proton irradiated samples, respectively.

We also measured the reverse recovery characteristics when switching from $+1$ V to a range of reverse biases and found recovery times of order 20–30 ns for both control and proton irradiated rectifiers, as shown in Fig. 7. We have reported previously in electron irradiated rectifiers that the reverse recovery shows little change with radiation dose,$^{25}$ since the minority carrier lifetime (which controls the carrier storage time in the intrinsic layer) is already small in Ga$_2$O$_3$.

**IV. SUMMARY AND CONCLUSIONS**

Ga$_2$O$_3$ rectifiers were irradiated with 10 MeV protons to a fixed fluence of $10^{14}$ cm$^{-2}$. The carrier removal rate in the

![Fig. 3](image1.png)

**Fig. 3.** (Color online) $C^{-2}$-V characteristics of Ga$_2$O$_3$ rectifiers before and after proton irradiation and subsequent annealing at either 300 or 450 $^\circ$C.

![Fig. 4](image2.png)

**Fig. 4.** (Color online) On/off ratio as a function of reverse bias voltage for rectifiers before and after proton irradiation and subsequent annealing at either 300 or 450 $^\circ$C.

![Fig. 5](image3.png)

**Fig. 5.** (Color online) Carrier removal rate for radiation damage of Ga$_2$O$_3$ measured in this work and also reported previously, as a function of radiation type and energy. Similar data for various types of GaN-based high electron mobility transistors and thin films are shown for comparison.

![Fig. 6](image4.png)

**Fig. 6.** (Color online) Optical image of wire-bonded Ga$_2$O$_3$ rectifier (top) and measured diffusion length as a function of temperature for control and proton irradiated rectifiers (bottom).
The drift region of the rectifiers was 235.7 cm$^{-1}$ under these conditions. The reverse breakdown voltage increases in response to a reduction in channel carrier density and the on/off ratio and minority carrier diffusion length are also degraded. Recovery of the damage begins at 300 °C, while annealing at 450 °C brings significant recovery of carrier density. The carrier removal rates are Ga$_2$O$_3$ are comparable to those in GaN under similar conditions.

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