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ABSTRACT
The impact of high energy neutron irradiation on the creation of specific radiation-induced deep level defect states and the ensuing influence of these defects on the electronic properties of (010) β-Ga$_2$O$_3$, doped with Ge and grown by plasma-assisted molecular beam epitaxy, were explored. A significant amount of carrier removal was observed in the irradiated samples exposed to 1 MeV equivalent neutron fluences of 8.5 × 10$^{14}$ cm$^{-2}$ and 1.7 × 10$^{15}$ cm$^{-2}$, which suggests the formation of compensating defects by neutron irradiation. Using a combination of deep level transient/optical spectroscopy (DLTS/DLOS) techniques to probe the entire ~4.8 eV bandgap with high energy resolution, three specific trap states were introduced by neutron irradiation at E$_T$-1.22 eV, E$_T$-2.00 eV, and E$_T$-0.78 eV. Of these, the former two states, observed by DLOS, were also present prior to irradiation, whereas the trap at E$_T$-0.78 eV, observed by DLTS, was not evident prior to neutron irradiation. The radiation dependence suggests that intrinsic point defects are the likely physical sources for these states. Subsequent lighted capacitance-voltage measurements further revealed that these three states are the source for the observed strong carrier compensation, with the trap at E$_T$-2.00 eV appearing as the strongest compensating defect for the neutron-irradiated β-Ga$_2$O$_3$.

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Beta phase gallium oxide (β-Ga$_2$O$_3$) is emerging as a promising wide bandgap material for high power electronics and ultraviolet optoelectronics, due to its ~4.8 eV bandgap, a large predicted breakdown field of ~8 MV/cm, a projected Baliga figure of merit greatly exceeding those of GaN and SiC counterparts, and the availability of large area, melt-grown free-standing native substrates. The ease of n-type doping and the ability to form β-(Al$_{1-x}$Ga)$_2$O$_3$/Ga$_2$O$_3$ heterojunctions have led to promising device demonstrations, including metal-semiconductor field effect transistors (MESFETs), metal-oxide field effect transistors (MOSFETs), delta-doped FETs, Schottky diodes, and (Al$_{1-x}$Ga)$_2$O$_3$/Ga$_2$O$_3$ modulation-doped field effect transistors (MODFETs). Moreover, the predicted radiation hardness of β-Ga$_2$O$_3$, with displacement energies of 25 eV and 28 eV calculated for Ga and O, respectively, compare favorably with GaN, for which displacement energies of ~20 eV for Ga and 10–20 eV for N have been reported. As a result, β-Ga$_2$O$_3$ is of great interest for device applications in harsh radiation environments.

Thus, it becomes of immediate interest to understand how environmental effects and harsh operating conditions can play a part in β-Ga$_2$O$_3$ device performance, and the role of radiation-induced crystalline defects has become a targeted topic. However, the study of defects, either grown-in or due to radiation and other harsh environments, is still relatively immature, especially when compared to wide bandgap semiconductors such as GaN and SiC, which have benefited from decades of study.
Filling this need is particularly important now since the $\beta$-Ga$_2$O$_3$ epitaxial growth field is rapidly evolving; understanding growth-related defects pre- and postradiation for different epitaxial device structures will be needed. Already, $\beta$-Ga$_2$O$_3$ materials and device structures are being grown by molecular beam epitaxy (MBE), low-pressure chemical vapor deposition (LPCVD), metal-organic chemical vapor deposition (MOCVD), and halide vapor phase epitaxy (HVPE). To date, there have been reports on electron irradiation of $\beta$-Ga$_2$O$_3$ revealing carrier compensation and on gamma radiation-induced degradation of gate insulators and surface passivation for $\beta$-Ga$_2$O$_3$ MOSFETs. Defect generation due to proton irradiation has been reported in edge-defined film-fed growth (EFG)-grown $\beta$-Ga$_2$O$_3$ substrates, MBE-grown homoepitaxial materials, and HVPE-grown materials (including alpha particles) in studies that employed deep level transient spectroscopy (DLTS) to probe defect states within approximately 1–1.5 eV of the conduction band edge or lightly capacitance-voltage (LCV) measurements, which were used up to an illumination energy of 3.4 eV for the ~4.8 eV bandgap material. Neutron irradiation effects have been recently reported using depth-resolved cathodoluminescence and surface photovoltage spectroscopy that were used to optically detect defects that exist with emission energies greater than 1.1 eV in the $\beta$-Ga$_2$O$_3$ bandgap. Our previous work on neutron irradiation-induced defects involved both DLTS and deep level optical spectroscopy (DLOS), the combination of which allows quantitative defect spectroscopy across the entire $\beta$-Ga$_2$O$_3$ bandgap, which was applied to EFG (010) $\beta$-Ga$_2$O$_3$. However, a comprehensive report on irradiation-induced defects throughout the entire ~4.8 eV bandgap of epitaxially grown $\beta$-Ga$_2$O$_3$ materials is still lacking. Given that the grown-in deep level defect spectra of epitaxial and bulk substrate gallium oxide are known to be different, understanding how high energy neutron irradiation might affect epitaxial materials differently is of interest, and this work focuses on that question. Here, both DLTS and DLOS measurements are used before and after irradiation at several doses to detect and quantitatively characterize irradiation-induced defect states and defect-specific introduction rates throughout the 4.8 eV bandgap of Ge-doped $\beta$-Ga$_2$O$_3$ homoepitaxial layers grown by plasma-assisted molecular beam epitaxy (PAMBE).

The epitaxial structures were grown by PAMBE on commercially available (Tamura) EFG-grown $\beta$-Ga$_2$O$_3$ Sn-doped (010) substrates. The test structure consisted of, from bottom up, highly Sn-doped (010) substrates (approximate doping ~5 x 10$^{15}$ cm$^{-3}$), ~200 nm of n+ $\beta$-Ga$_2$O$_3$:Ge to support a subsequently formed n-Ohmic contact, followed by ~450 nm of lightly Ge-doped $\beta$-Ga$_2$O$_3$ to serve as the test layer for the high sensitivity trap spectroscopy measurements. Note that n-type doping using Ge is of interest since Ge$^{3+}$ is a favorable donor for $\beta$-Ga$_2$O$_3$ due to its close size match with the Ga$^{3+}$ cation, and the Ge oxides have a higher vapor pressure compared to that of Si oxides, suggesting that problematic oxidation of the group IV source in MBE growth could be mitigated. Secondary ion mass spectrometry (SIMS) measurements revealed the n- and n+ Ge concentrations are ~5–6 x 10$^{16}$ cm$^{-3}$ and ~1 x 10$^{18}$ cm$^{-3}$ (Fig. 1), making this ideal for DLTS and DLOS studies. The PAMBE growth for the n- and n+ layers was performed within a slightly Ga-rich regime using a substrate temperature of 600 °C and a Ga flux (beam-equivalent pressure, BEP) of 1.0 x 10$^{-7}$ Torr. The n- and n+ layers were grown at Ge effusion cell temperatures of 530 and 625 °C, respectively. Further information regarding the PAMBE growth methods and conditions of $\beta$-Ga$_2$O$_3$ have been previously published. After growth, the sample was processed into arrays of ~290 μm x 290 μm diodes by depositing an 8 nm semitransparent Ni-Schottky contact that also serves to facilitate optical penetration for DLOS measurements. To form the Ohmic contact, a ~430 nm Ti/Al/Ni/Au Ohmic metal stack was deposited on the underlying n+ contact layer that was exposed by BCl$_3$-based inductively coupled plasma-reactive ion etching (ICP-RIE). This standard Schottky structure has been reported in our previous work.

Prior to irradiation, devices were screened using current-voltage (I-V) and capacitance-voltage (C-V) measurements to ensure that high quality diodes were used for this study and internal photoemission (IPE) was used to assess the Ni/$\beta$-Ga$_2$O$_3$ Schottky barrier height (SBH). Deep level spectroscopy measurements and the electrical measurements were performed in the same test diodes before and after irradiation to make reliable comparisons before and after irradiation. The IPE measurements were performed at 300 K using multiple diodes to obtain reliable statistics where the error magnitude was determined from the standard deviation of the dataset as described in earlier work. DLTS measurements were used to quantitatively detect defect states present within ~1 eV from the conduction band edge, which is based on controlling thermally stimulated emission of electrons to the conduction band from individual defect states in the bandgap. DLOS measurements were used to explore individual optical defect transitions (deep level photoemission) to the conduction band from states within the remainder of the ~4.8 eV bandgap that is not probed by DLTS due to its thermal emission limits. Both DLTS and DLOS measurements were
performed using the same filling bias of 0.00 V and a reverse bias of $-1.00 \text{ V}$ on the Schottky diodes but with different filling pulse durations of 10 ms and 10 s, respectively. Both DLTS and DLOS monitor the effect of trap emission on the transient and steady state junction capacitance. The DLTS data were analyzed using the conventional double boxcar method for multiple windows between 0.8 s and 1000 s to ensure a high degree of accuracy throughout the scanned temperature range of 77 K–430 K. The magnitude of the individual capacitance peak heights were used to calculate DLTS trap concentrations, and here, we have accounted for the modulated depletion region volume for each particular trap state, which can change for different trap energy levels as a function of the applied bias values (the so-called lambda correction). DLOS measurements were performed at 300 K and used a tunable, monochromatized light source to provide photoexcitation of individual trap states. A 600 W quartz halogen ($\lambda_{QH}$) lamp was used to provide incident photons with energies in the range from 0.50 eV to 2.00 eV, and a 1000 W Xe-lamp was used to provide incident photons with energies in the range from 1.20 eV to 5.00 eV. Two monochromators were used to step the photon energies from 0.50 eV to 2.00 eV and 1.20 eV–5.00 eV in 0.02 eV for the $\lambda_{QH}$ and Xe-lamp, respectively. The concentration of each DLOS-detected state is obtained from the individual step-heights in steady state photocapacitance (SSPC) spectrum when an incident photon energy resonates with the emission of a trapped electron from a state to the conduction band. However, the precise energy level for each SSPC onset is obtained by analyzing the photocapacitance transient behavior and fitting the optical cross section associated with the onset using the well-known Pässler model, which provides the Franck-Condon energy ($D_{FC}$) that accounts for the degree of lattice relaxation associated with each of the trap states. Full details on the trap spectroscopy measurements and analysis methods by DLTS and DLOS can be found in earlier reports.

Prior to irradiation, the $\beta$-$\text{Ga}_2\text{O}_3$ devices were screened using I-V and C-V measurements to ensure the suitability of Schottky diode quality used for this study. The 1 MHz C-V extracted doping of these epitaxial $\beta$-$\text{Ga}_2\text{O}_3$ samples yielded uniform doping values of $\sim 8-9 \times 10^{16}$ cm$^{-3}$ across the test layer. This is higher than the intentional Ge concentration from SIMS in Fig. 1, which additionally shows no evidence of out-diffusion of Sn into the epitaxial test layer from the highly Sn-doped (010) substrate during the growth from the lack of a Sn signal above the SIMS detection limit of 2 ppm. Some unintentional background dopants, such as Si, might be contributing to the additional doping as shown from SIMS in Fig. 1.

To perform the irradiation exposure at multiple doses, the sample was subsequently diced into two pieces, and each piece was exposed separately with fast neutrons (energy > 0.5 eV) to a different dose achieved by irradiating for different time durations, 30 min and 60 min, at 450 kW power in the Ohio State University Research Reactor (OSURR) Rabbit facility. The displacement damage dose, $D_{disp}$, was calculated to be $2.5 \times 10^{11}$ MeV g$^{-1}$ and $5.0 \times 10^{11}$ MeV g$^{-1}$ for the 30 min and 60 min of exposure, respectively. The 1 MeV neutron equivalent fluences were obtained as $8.5 \times 10^{14}$ cm$^{-2}$ and $1.7 \times 10^{15}$ cm$^{-2}$ for these respective lower and higher displacement damage doses. It is to be noted that for this fast neutron energy range (1 eV–20 MeV), the mean free path for scattering interaction ($\lambda$) is estimated to be greater than 1 cm in $\beta$-$\text{Ga}_2\text{O}_3$ using the Monte Carlo N-Particle Transport Code (MCNP) software, which is well beyond the entire epitaxial film of ~450 nm thickness. Details of this neutron irradiation for $\beta$-$\text{Ga}_2\text{O}_3$ are available in previous reports.

**FIG. 2** IPE showing similar Schottky barrier height $-1.40 \pm 0.02 \text{ V}$ before and after neutron irradiation revealing that the SBH is unaffected with the both fluences used in this study.

**FIG. 3** J-V characteristics prior to and after neutron irradiation showing similar Schottky diode behavior for 1 MeV equivalent fluences of (a) $8.5 \times 10^{14}$ cm$^{-2}$ and (b) $1.7 \times 10^{15}$ cm$^{-2}$, respectively, revealing the diode quality was not affected by irradiation.
After the neutron irradiation, the same diodes were screened again by I-V, C-V, and IPE measurements to assess the device quality. The Ni/β-Ga2O3 SBH values extracted using IPE were unaffected with a value of 1.40 ± 0.02 V for both doses (Fig. 2), which ensured that the neutron irradiation did not degrade the Schottky barrier quality. The reverse leakage currents of the Schottky diodes were fairly similar, on the order of ∼1 μA/cm², before and after irradiation for both doses as shown in Fig. 3. However, strong carrier removal effects occurred from the irradiation effects as indicated from the C-V measurements shown in Fig. 4. The C-V extracted net carrier concentration profiles (n = N⁺ − N⁻) are presented in Fig. 5(a). A reduction in overall carrier concentration of ∼1.5 × 10¹⁶ cm⁻³ and ∼3.2 × 10¹⁶ cm⁻³ is observed compared to the as-grown net doping concentrations for the lower and higher neutron fluences, respectively. This translates to a carrier removal rate of ∼19 ± 0.3 cm⁻¹ estimated with respect to 1 MeV equivalent neutron fluences [Fig. 5(b)]. However, the carrier removal rate, if calculated using the more simplistic approach of integrated neutron fluences gives a carrier removal rate of ∼7.9 ± 0.1 cm⁻¹ for PAMBE-grown β-Ga2O3, which is similar to GaN values of 1–10 cm⁻¹ found using the same method as reported in Ref. 38. Given that this latter, simplistic approach does not account for the damage cross section for a particular neutron energy, we have considered the 1 MeV equivalent neutron fluences throughout as described in our prior work,²⁶ which considers both neutron flux and damage cross section as a function of neutron energy. This method gives a higher carrier reduction rate compared to the previously used simplistic method of involving only integrated neutron fluences but provides a more accurate and meaningful approach since both the neutron flux and damage cross section are important parameters to evaluate the displacement damages performed by a particular neutron energy present in the fast neutron spectra. Regardless of the calculation method, the significant carrier reduction implies the creation of compensating traps in the bandgap for which DLTS and DLOS measurements were employed to qualitatively and quantitatively detect the compensative trap centers, as discussed next.

DLTS measurements were employed first to detect defect states in the upper ∼1 eV part of the bandgap for which the spectra of before and after irradiation are shown Fig. 6(a), and the trap concentrations are provided in Table I. Before irradiation, the DLTS spectra consisted of shallow states at E Cv-0.21 eV, E Cv-0.42 eV, E Cv-0.60 eV, and E Cv-0.96 eV with capture cross sections of 6.2 × 10⁻¹⁵ cm², 1.1 × 10⁻¹⁵ cm², 1.3 × 10⁻¹⁴ cm², and 2.0 × 10⁻¹⁵ cm², respectively. The level near E Cv-0.21 eV was previously observed in Ge-doped epitaxial samples and has an energy, and may be associated with localized states for Ge donor dopants incorporated into octahedral Ga₃ sites as opposed to the tetrahedral Ga₄ sites.²⁹ After neutron irradiation, two new traps not seen in this material in the as-grown state have emerged, one at ∼E Cv-0.78 eV with a concentration on the order of ∼10¹⁵ cm⁻³ and a capture cross section of 7.0 × 10⁻¹⁴ cm², and a state at ∼E Cv-0.33 eV with a concentration on the order of ∼10¹⁵ cm⁻³ and a capture cross section of 2.5 × 10⁻¹⁵ cm². The ∼E Cv-0.33 eV trap had not been previously reported. However, there have been several previous reports of the ∼E Cv-0.78 eV state, labeled E Cv+, seen after proton irradiation of β-Ga₂O₃ substrates and also in nonirradiated MESFETs grown by PAMBE. The Arrhenius data of these reports (including the capture cross section) match what are shown in Fig. 6(a) after neutron irradiation, suggesting that the source of this level is probably related to an intrinsic...
The point defect [Fig. 6(b)]. It is important to note that this region of the β-Ga2O3 bandgap is crowded with trap data reported from a number of groups, which can confuse the interpretation of data in the literature. As an example, an entirely distinct trap with an energy of $-E_{C}-0.8$ eV, labeled $E_2$, has also been reported by several groups, including ours, but the Arrhenius data over a wide temperature for this trap are entirely distinct from the one we are reporting here. Indeed, the $-E_{C}-0.8$ eV ($E_2$) trap has been attributed to Fe impurities that can be present in various materials, and this discernment has been noted by several groups. Getting back to the $E_2$-0.78 eV ($E_2^*$) trap, theoretical calculations have predicted that gallium vacancies ($V_{Ga}$), gallium vacancy-interstitial complexes ($V_{Ga}^{i}$), or antisites ($Ga_{O}$) have energies near this experimentally determined value, and it is reasonable that these intrinsic defects can form upon high energy particles due to displacement events from Ga-sites. Finally, for completeness, there is a broad feature in the DLTS scan that appears after irradiation whose peak is beyond our DLTS temperature range of 430 K.

We now turn to DLOS to explore the remaining majority of the bandgap. DLOS detected two trap states, one at $E_{C}-2.00$ eV and another at $E_{C}-4.49$ eV for which trap energies and $D_{TC}$ values are extracted from the optical cross section analysis using the Pässler model within $\pm 5\%$ error of the fitting (Fig. 7). For the $E_{C}-4.49$ eV state, a sharp optical cross section spectrum is observed with a small extracted $D_{TC}$ = 0.04 eV. The $E_{C}-1.22$ eV state is associated with a high degree of lattice-coupling with $D_{TC}$ = 0.48 eV, and the near midgap state $E_{C}-2.00$ eV reveals $D_{TC}$ = 0.56 eV (Fig. 7), typical for deeper states in wide-bandgap materials. Figure 7 also demonstrates the magnitudes of optical cross sections of the detected states, which reveals a significantly smaller cross section for $E_{C}-1.22$ eV and $E_{C}-2.00$ eV states compared to the near valence band state of $E_{C}-4.49$ eV. A small optical cross section could result from a variety of physical properties, including the spatial size of the defect, its charge state, and large lattice relaxation causing substantial localization of wavefunctions at defect states with strong phonon-coupling. Any of these can lead to relatively slow optical emission processes and partial emptying of the trap states as reported earlier in

### Table I. Summary of trap energy levels and their concentrations before and after neutron irradiation in the PAMBE-grown Ge-doped epitaxy for the two fluence cases.

| Trap energy (eV) | $E_{C}-0.21$ | $E_{C}-0.33$ | $E_{C}-0.42$ | $E_{C}-0.60$ | $E_{C}-0.78$ | $E_{C}-0.96$ | $E_{C}-1.22^a$ | $E_{C}-2.00^b$ | $E_{C}-4.49$ |
|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| **Trap concentration (cm$^{-3}$) for a 1 MeV equivalent fluence of 8.5 x 10$^{14}$ cm$^{-2}$** |
| **Prerad** | $3 \times 10^{14}$ | Undetected | $4 \times 10^{13}$ | $4.4 \times 10^{13}$ | Undetected | $1 \times 10^{14}$ | $1.3 \times 10^{13}$ | $2.72 \times 10^{16}$ | $\sim 4.5 \times 10^{16}$ |
| **Postrad** | $3 \times 10^{14}$ | $3.8 \times 10^{13}$ | $4 \times 10^{13}$ | $4.4 \times 10^{13}$ | $6 \times 10^{14}$ | Unresolved | $7.5 \times 10^{14}$ | $2.86 \times 10^{16}$ | $\sim 4.5 \times 10^{16}$ |
| **Trap concentration (cm$^{-3}$) for a 1 MeV equivalent fluence of 1.7 x 10$^{15}$ cm$^{-2}$** |
| **Prerad** | $3 \times 10^{14}$ | Undetected | $3.5 \times 10^{13}$ | $4 \times 10^{13}$ | Undetected | $1.6 \times 10^{14}$ | $4 \times 10^{14}$ | $3.47 \times 10^{16}$ | $\sim 4.5 \times 10^{16}$ |
| **Postrad** | $3 \times 10^{14}$ | $5.1 \times 10^{13}$ | $3.5 \times 10^{13}$ | $4 \times 10^{13}$ | $1.5 \times 10^{15}$ | Unresolved | $1.5 \times 10^{15}$ | $3.88 \times 10^{16}$ | $\sim 4.5 \times 10^{16}$ |

$^a$DLOS trap concentrations are likely to be underestimated due to the very small optical cross section of these states.
previous work, and this affects the ability to achieve full saturation by stimulated optical emission processes, such as steady state photocapacitance (SSPC) and LCV. The SSPC data correlating to the DLOS-detected traps before and after both neutron irradiation fluences are plotted in Fig. 8. Considering the aforementioned small optical cross sections of the DLOS-detected deeper states, we turned to LCV measurements to sequentially photoionize each defect state at 300 K under sub-bandgap monochromatic illumination for 2.5 h before implementation of C-V sweep. The photon energies were chosen such that they can emit electrons from all energy levels less than the photon energy, and thus, the difference in net doping between each sequentially applied illumination will provide the net carrier removal performed by that state whose energy level exists between the sequential energy steps. With this in mind and noting the DLOS-detected energy levels, the LCV measurements were performed for each of the following incident photon energies: in dark (no illumination) and then under illumination with single energies of 1.80 eV, 4.00 eV, and 4.70 eV photons, with each illumination for 2.5 h. The LCV results are shown in Fig. 9, and the resultant LCV-measured trap concentrations are summarized in Table I. First, the C-V was applied in the dark, holding at reverse bias with a delay of 2.5 h to thermally ionize traps that are closer to the conduction band edge, i.e., those detected by DLTS. However, this “dark-hold” step itself resulted in a carrier concentration recovery of ~7 × 10^{14} cm^{-3} and ~1.5 × 10^{15} cm^{-3} for the samples receiving 1 MeV neutron-equivalent fluences of 8.5 × 10^{14} cm^{-2} and 1.7 × 10^{15} cm^{-2}, respectively. In contrast, no such change was observed after LCV measurements were made on the preirradiated samples. These concentrations are comparable to the concentrations of the irradiation-induced DLTS-detected states (E_C-0.78 eV and the deeper states near ~1 eV) for these respective fluences, identifying a correlation that may suggest that these two states contribute to irradiation-induced carrier compensation. Next, for the 1.80 eV illumination for which the excitation energy is sufficient to depopulate the E_C-1.22 eV trap but keep the deeper states at E_C-2.00 eV and E_C-4.49 eV unaffected (filled), there is a slight increase in net doping in the irradiated samples of ~7.5 × 10^{14} cm^{-3} and ~1.5 × 10^{15} cm^{-3} in the lower and higher neutron fluences, respectively. This indicates that the E_C-1.22 eV trap is also a compensating center and comparable to the traps at E_C-0.78 eV and ~E_C-1 eV. For the 4.00 eV illumination, the E_C-2.00 eV and E_C-1.22 eV trap levels are emitted while keeping the E_C-4.49 eV level unaffected, a significant increase in the net doping concentration is observed for the irradiated samples. This implies that the state at E_C-2.00 eV is a strong source of carrier compensation. Finally, with the 4.70 eV illumination that would affect the ~E_C-4.4 eV, the same increase in net doping was observed both before and after irradiation, suggesting that while this state appears to contribute to carrier removal, it shows no dependence on neutron irradiation. What this might...
mean in terms of identifying its physical source is currently under investigation. Figure 10 shows the change in irradiation-introduced trap concentrations for the states at $E_C-0.33$ eV, $E_C-0.78$ eV, $E_C-1.22$ eV, and $E_C-2.00$ eV as a function of neutron fluence, where the introduction rates were found to be $0.03 \pm 0.004$ cm$^{-1}$, $0.85 \pm 0.05$ cm$^{-1}$, $0.89 \pm 0.02$ cm$^{-1}$, and $2.31 \pm 0.15$ cm$^{-1}$, respectively. The summation of these individual introduction rates is lower than the carrier removal rate of $\sim 19 \pm 0.3$ cm$^{-1}$, which we attribute to the afore-mentioned small optical cross sections and difficulty in achieving their optical saturation, resulting in underestimation of trap concentrations for the $E_C-1.22$ eV and $E_C-2.00$ eV states. The large differences between the carrier removal rates and the summation of individual introduction rates in trap states detected by LCV or photocapacitance measurements have also been reported earlier in HVPE-grown $\beta$-Ga$_2$O$_3$ irradiated with proton and alpha particles.$^{23}$

A diagrammatic representation of the distribution of bandgap states in the PAMBE sample for the higher fluence case is shown in Fig. 11 in order to more easily visualize the different radiation sensitivities for each defect state. Regarding physical sources for the radiation-sensitive states, we here overview current density functional theory (DFT) calculation results to observe possible correlations but noting that theoretical calculations are continuing to be refined at the time of this writing.$^{21,44–51}$ Density functional

![FIG. 10. Irradiation-induced trap concentration plotted with respect to the 1 MeV equivalent fluences of 8.5 x 10^{15} cm$^{-2}$ and 1.7 x 10^{16} cm$^{-2}$ for the $E_C-0.33$ eV, $E_C-0.78$ eV, $E_C-1.22$ eV, and $E_C-2.00$ eV states. The slopes provide the introduction rates as $0.03 \pm 0.004$ cm$^{-1}$, $0.85 \pm 0.05$ cm$^{-1}$, $0.89 \pm 0.02$ cm$^{-1}$, and $2.31 \pm 0.15$ cm$^{-1}$, respectively. The summation of the individual introduction rates is lower than the carrier removal rate of $\sim 19 \pm 0.3$ cm$^{-1}$ due to an underestimation of the trap concentration from the DLOS-detected compensating centers, $E_C-1.22$ eV and $E_C-2.00$ eV, which results from their slow optical emission rates.](image1)

![FIG. 11. Summary of trap concentration, showing the sensitivity of the $E_C-1.22$ eV and $E_C-2.00$ eV states for a 1 MeV equivalent fluence of 1.7 x 10^{16} cm$^{-2}$. Note that the concentrations of the DLOS traps before and after irradiation are likely even greater (but at the same ratio) than shown here due to their small optical cross sections causing an underestimation of these values.](image2)
measurements identify these irradiation-induced trap states to be the most strongly correlated with the observed carrier compensa-
tion mechanism. The ubiquitous state at $E_C-4.4$ eV from the DLOS measurement was insensitive to radiation, inviting additional studies to clarify its origin.

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