Applied Physics Letters ARTICLE scitation.org/journal/apl

Correlation between non-ionizing energy loss and production rate of electron trap at $E_C - (0.12–0.20)$ eV formed in gallium nitride by various types of radiation

Cite as: Appl. Phys. Lett. **122**, 012106 (2023); doi: 10.1063/5.0128709
Submitted: 30 September 2022 · Accepted: 15 December 2022 ·
Published Online: 6 January 2023

View Online Export Citation CrossMark

Keito Aoshima,[1,a)] Masahiro Horita,[1,2] and Jun Suda[1,2]

AFFILIATIONS

[1]Department of Electronics, Nagoya University, Nagoya 464-8601, Japan
[2]Institute of Materials and Systems for Sustainability (IMaSS), Nagoya 464-8601, Japan

[a)]Author to whom correspondence should be addressed: aoshima.keito.b3@s.mail.nagoya-u.ac.jp

ABSTRACT

Production rate (PR = trap concentration/incident fluence) of traps formed by energetic particles is important for predicting device degradation caused by radiation when developing radiation-resistant devices. We demonstrate a clear correlation between non-ionizing energy loss (NIEL) and PR of an electron trap at about 0.12–0.20 eV below the conduction band edge [$E_C - (0.12–0.20)$ eV] for various types of energetic particles in gallium nitride (GaN). NIEL values in GaN for electrons, protons, and α-rays were calculated using a screened-relativistic treatment, and NIEL values for gamma-rays were calculated by simulating slowed-down spectra due to shielding material. To obtain the PRs of the electron trap, ^{60}Co gamma-rays with an average photon energy of 1.25 MeV and electron beams with energies from 137 keV to 2 MeV were irradiated onto n-type GaN Schottky barrier diodes. We measured the concentration of an electron trap at $E_C - (0.13–0.14)$ eV using deep-level transient spectroscopy. We also used the PRs of electron traps with similar energy levels of $E_C - (0.12–0.20)$ eV from previous studies on electrons, protons, and α-rays irradiated on GaN. All the trap PRs were proportional to the NIEL in a range of eight orders of magnitude, which confirms that the energy levels formed by various energetic particles have the same origin of being generated by atomic displacements. The obtained relationship coefficient between the NIEL and PRs of the trap is useful for predicting the degradation of GaN-based devices due to traps formed by various kinds of radiation.

The electrical and optical characteristics of electron devices in harsh radiation environments, such as space, nuclear reactors, and particle accelerators, become degraded by point defects formed by energetic particles.[1] Energetic particles lose energy through interactions with matter, and part of the energy lost to nuclei causes atomic displacement, which leads to the generation of vacancy-interstitial pairs (Frenkel pairs). To predict the degradation of semiconductor devices due to radiation and to design and development superior radiation-resistant electron devices, it is necessary to understand trap levels in semiconductors introduced by radiation.

For the past two decades, wide-bandgap semiconductor gallium nitride (GaN) has been extensively studied for use in light-emitting devices, high-frequency devices, and power switching devices.[2–4] High electron mobility transistors (HEMTs) are already used for RF power amplifiers in space satellites. GaN is favored as a material for radiation-resistant devices due to its wide bandgap,[5] strong ionic-covalent bonds,[6] and large predicted displacement energies for gallium (Ga) and nitrogen (N) in GaN[7] (the theoretical average values for all incident directions are 109 eV for N and 34 eV for Ga). To predict the degradation by energetic particles of GaN-based electron devices and to develop GaN-based radiation-resistant devices, it is important to evaluate traps formed by radiation in GaN. Deep-level transient spectroscopy (DLTS),[8] which provides a direct probe to evaluate concentrations, activation energies, and carrier capture cross sections of trap levels, is commonly used. Our group investigated electron traps formed by gamma-rays[9,10] and electron beams (EBs)[11,12] irradiation onto n-type GaN by DLTS. The obtained results showed that some of the traps formed by the energetic particles are close energy levels in the bandgap in GaN. For instance, gamma-ray irradiation with an average photon energy of 1.25 MeV to GaN formed an energy level at

0.14 eV below the conduction band minimum ($E_C - 0.14$ eV) and an EB with an energy of 400 keV to GaN formed an energy level at $E_C - 0.13$ eV. The origin of the energy levels was speculated to be nitrogen vacancy (V_N)-related defects based on the results of EB irradiation with energies sufficient to cause only nitrogen atom displacements.[12] Some previous DLTS studies of electron traps in GaN formed by various types of energetic particles, such as electrons, protons, and α-rays, reported similar energy levels [$E_C - (0.12–0.20)$ eV][13–18] with different trap production rates (PRs = trap concentration/irradiation fluence). From the energy perspective, the deep traps observed for the various types of radiation may have the same origin, namely, V_N-related defects. It should be noted that the similar energy level was also observed in silicon (Si)-implanted GaN.[19]

Displacement damage caused by interactions between nuclei and high-energy particles can be quantified by the non-ionizing energy loss (NIEL) $dE_{de}/d\chi$, where χ (usually in g/cm^2) is the product of the target density ρ and target thickness x. NIEL is the energy loss per unit length of the incident particles due to displacement processes. If the PRs of the traps formed by different types of radiation can be related based on the NIEL, identifying traps and predicting the PRs for other radiation sources or energies should be possible.

For Si and gallium arsenide (GaAs), some reports have demonstrated that the device degradation related to defects formed by radiation correlates with the NIEL.[20,21] In addition, there have been few reports comparing NIELs with the PRs of traps formed by EB and proton beam (PB) in Si and GaAs, while ranges of NIEL values in these comparisons are quite narrow (less than one order of magnitude of NIEL).[22,23] Although there have been few studies comparing NIELs with degradation of SiC-based device, some relationships between NIEL and carrier removal rate,[24] and NIEL and carrier lifetime[25] have been demonstrated. For GaN, there have been only a few reports associating device degradation with NIEL; for instance, a report has evaluated the degradation of GaN-based light-emitting diodes by PB irradiation.[26] There have been no reports comparing NIEL with PRs of traps formed in GaN by various types of radiation.

In this study, we evaluated whether the NIEL approach can be applied to PRs of traps formed by various types of radiation in GaN. We evaluated the energy levels at $E_C - (0.12–0.20)$ eV reported for various types of radiation as a model case. The NIEL values for various types of radiation in GaN were calculated. The NIEL values for electrons, protons, and α-rays were calculated based on a screened-relativistic (SR) treatment.[27] To calculate the NIEL of gamma-rays, the slowed-down spectrum, i.e., the count of electrons generated by Compton scattering in shielding materials and irradiated onto GaN, was simulated by a Monte Carlo method using GEANT4.[28] PRs of traps formed by different energetic particles were evaluated by DLTS. Irradiation of gamma-rays with a photon energy of 1.25 MeV and EBs in the energy range 137–2 MeV with various incident fluences onto GaN Schottky barrier diodes (SBDs) was performed to prepare irradiated samples. Previously reported PRs for irradiation by electrons, protons, and α-rays onto n-type GaN were also taken into consideration. From a comparison of the PRs with the NIEL, it was found that the PRs are proportional to the NIEL for a range of NIEL values of eight orders of magnitude.

The NIEL calculations for electrons, protons, and α-rays were performed based on a binary collision approximation using SR-NIEL, in which the displacement damage is calculated using an SR code,[27,29]

$$\frac{dE_{de}}{d\chi} = \frac{N}{A}\int_{E_d}^{T^{max}} TL(T)\frac{d\sigma(E,T)}{dT}\,dT\,, \tag{1}$$

where N is the Avogadro constant, A is the atomic weight, E is the kinetic energy of the incident particle, T and T^{max} are the recoil kinetic energy and the maximum energy transferred to the recoil nucleus, respectively, $L(T)$ is the Lindhard partition function, which describes the partition of the nuclear recoil (kinetic) energy, and $d\sigma(E,T)/dT$ is the differential cross section of scattering. Scattering due to the elastic Coulomb potential is dominant in the energy range considered. NIEL at low particle energies strongly depends on the displacement threshold energy, E_d, for Ga and N in GaN. We used an E_d value of 21.8 eV for N in GaN obtained from a series of experiments to evaluate the threshold irradiation energy of EB irradiation.[12] An E_d value of 22.0 eV for Ga was used, based on a theoretical calculation.[30] NIEL for the compound semiconductor GaN was obtained as a weighted sum with each material contributing proportionally to its atomic weight.[31] The calculated NIEL for electrons, protons, and α-rays in GaN as a function of particle energy is shown as blue, red, and purple lines in Fig. 1, respectively.

Gamma-rays with energies greater than several tens of keV cause three types of interactions with materials: photoelectric absorption, Compton scattering, and electron–positron pair production. The main interaction between gamma-rays with energies of about 1 MeV and materials with atomic number less than 30 is Compton scattering. Gamma photons can cause indirect atomic displacements by secondary electrons generated by Compton scattering interactions, which leads to a broad electron energy spectrum. For calculating the NIEL of gamma-rays, the spectrum of secondary electrons generated in surrounding (shielding) materials and irradiated on the target material

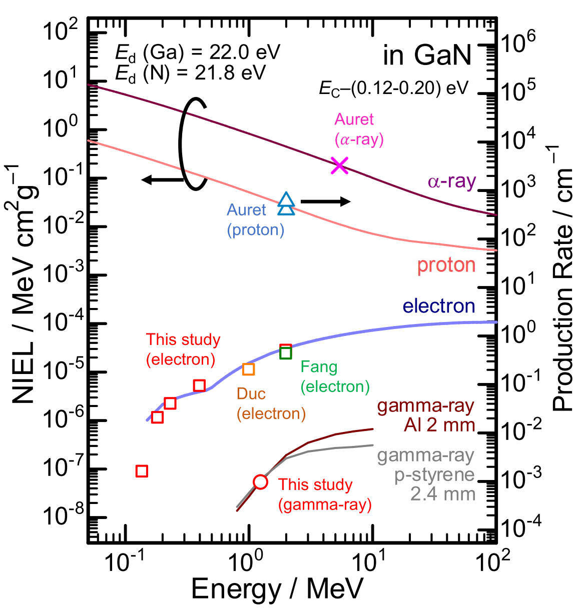

FIG. 1. Calculated NIEL for gamma-rays, electrons, protons, and α-rays as a function of particle energy shown as lines (left scale) and corresponding PRs of the trap formed by gamma-rays, electrons, protons, and α-rays with various energies plotted as a circle, squares, triangles, and a cross, respectively (right scale), based on the linear relationship between NIEL and PR for E_C – (0.12–0.20) eV as shown in Fig. 3.

(GaN) must be obtained. Usually, the NIEL of gamma-rays is calculated with the assumption that there are shielding materials [generally 2-mm-thick aluminum (Al) plate is employed]. Because most Compton scattering occurs in the surrounding materials rather than in the target material (~μ m), secondary electrons generated in GaN can be negligible. The number of atomic displacements depends on the secondary electron spectrum and the probability of these electrons to produce displacement atoms. The NIEL of gamma-rays can be expressed as[20]

$$\left(\frac{dE_{de}}{d\chi}\right)_\gamma = \int_0^{E^{max}} \frac{dS_c}{dE} \cdot \left(\frac{dE_{de}}{d\chi}\right)_e dE, \tag{2}$$

where S_c is the secondary electron spectrum and $(dE_{de}/d\chi)_e$ is the electron NIEL at a given electron energy E. The secondary electrons are slowed down by the shielding materials depending on the nature and thickness of the materials.[32] A Monte Carlo simulation code GEANT4[28] was applied to compute the slowed-down spectrum of secondary electrons generated by gamma-rays in the shielding materials. We used two kinds of materials, Al and polystyrene (material for semiconductor chip trays), for shielding materials in irradiation experiments. In our experiments, the GaN samples and Al shield were in contact, while there was an air layer of 1 mm between the samples and polystyrene shield. For the calculation, a standard electromagnetic physics model that takes photoelectric absorption, Compton scattering, and electron pair production into account was used. A cobalt-60 (^{60}Co) source, which was used as a gamma-ray source for the irradiation experiments, emits photons with energies of 1.17 and 1.33 MeV during radioactive decay.[33] We treated the gamma-rays as photons with an average energy of 1.25 MeV in the calculation.

Figure 2(a) shows slowed-down electron spectra produced by 1.25-MeV gamma-rays in Al with various thicknesses from 0.2 to 8 mm. The secondary electrons have a broad energy range up to about 1 MeV. The spectra saturated above a thickness of 1 mm, indicating that Compton electrons produced in Al at a distance larger than the practical range are absorbed by the Al. The calculated spectrum is in close agreement with the previously reported Monte Carlo calculation for 2-mm Al thickness.[34] The effect of shielding by a nickel (Ni) Schottky contact with a thickness of 400 nm between Al and GaN was also simulated because we formed Ni/GaN Schottky barrier diodes

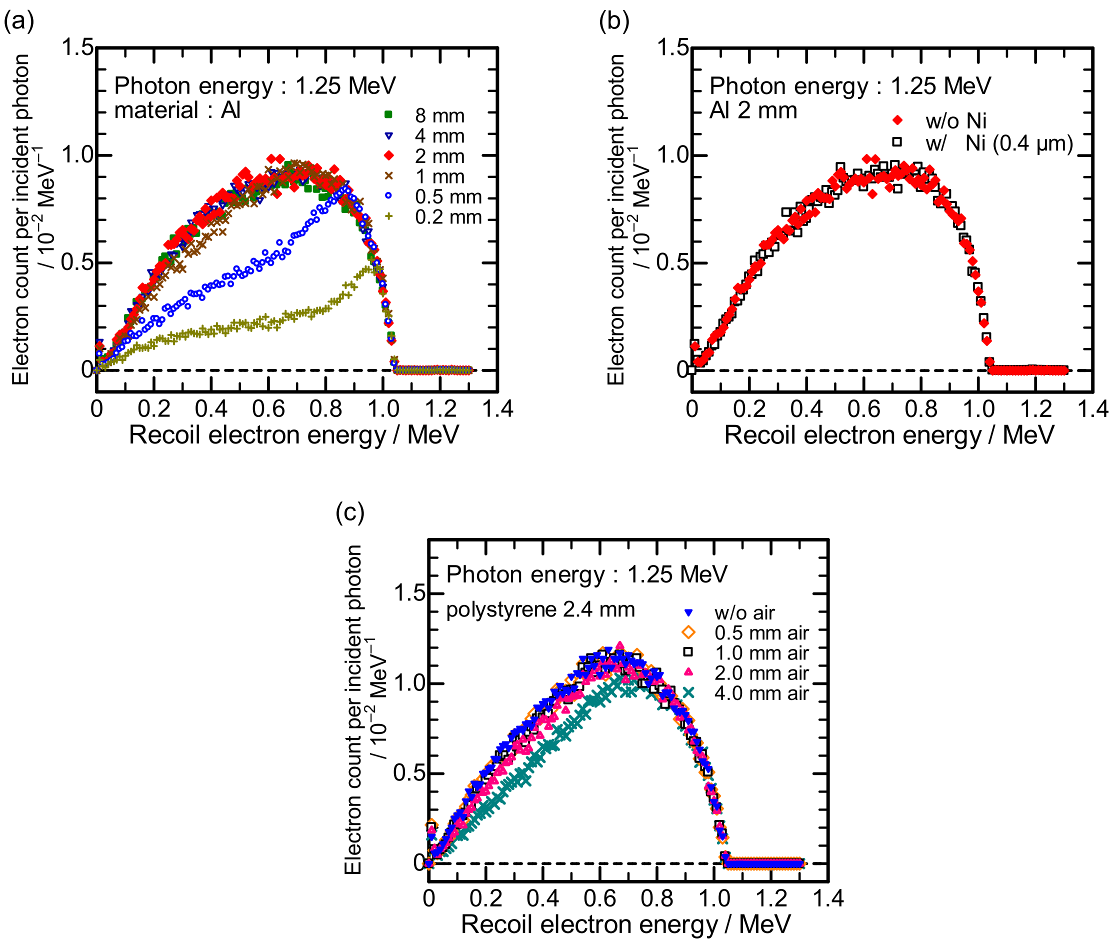

FIG. 2. Slowed down spectra of Compton electrons produced by gamma-rays with photon energy of 1.25 MeV: (a) Al thicknesses dependence (0.2, 0.5, 1.0, 2.0, 4.0, and 8.0 mm). (b) Effect of Ni metal between Al shield and GaN. (c) Effect of an air layer between polystyrene shield and GaN.

before irradiation. It was found that the shielding effect due to Ni can be negligible because the Ni layer is very thin. Figure 2(c) shows the slowed-down spectra for secondary electrons generated by 1.25-MeV gamma-rays in 2.4-mm-thickness polystyrene thorough an air layer with various thicknesses. For an air layer thickness less than 1 mm, the slowed-down spectra were almost identical to that without an air layer. Since the air layer thickness is 1 mm in our irradiation setting, we employed the calculation result without an air layer. The spectrum of 2.4-mm polystyrene without an air layer is higher than that of 2.0-mm Al in an energy range of 0.4–0.8 MeV, due to the density and atomic (molecular) weight of the materials.

NIEL_γ curves for GaN irradiated through Al and polystyrene calculated using Eq. (2) are shown in Fig. 1 as a brown line for 2-mm Al and a gray line for 2.4-mm polystyrene. The NIEL_γ is one order of magnitude less than the electron NIEL. Although NIEL_γ depends on the shielding materials, the NIEL_γ values for 1.25-MeV gamma-rays used for this experiment are very close; NIEL_γ for 2-mm Al is 5.4×10^{-8} MeV cm^2 g^{-1}, and for 2.4-mm polystyrene, it is 5.9×10^{-8} MeVc m^2 g^{-1}.

To measure the trap concentrations formed by gamma-ray and EB irradiation, Ni/n-GaN SBDs were fabricated on metalorganic vapor phase epitaxy (MOVPE)-grown n-type GaN on hydride vapor phase epitaxy (HVPE)-grown n-type GaN substrates. The devices consist of Ti/Al Ohmic contacts on the backside and Ni Schottky contacts on the epitaxial layer. The sintering of Ohmic contacts was performed before gamma-ray and EB irradiation to avoid the migration and reaction of irradiation-induced point defects via annealing. Gamma-irradiated samples were prepared by irradiating samples covered by 2-mm Al or 2.4-mm polystyrene with ^{60}Co gamma-rays. Various dose exposures, in Si-equivalent absorbed doses of 50–500 kGy [=47.4–474 kGy (GaN)], at a dose rate of about 10 kGy (Si)/h were performed, after fabrication of Schottky contacts by resistive heating evaporation. The relationship between the Si equivalent absorbed dose and photon fluence is expressed as 1 kGy (Si) = 1.9×10^{14} cm^{-2} using 2.7×10^{-3} m^2 kg^{-1} as the mass energy absorption coefficient of Si for 1.25-MeV photons.[35] EB-irradiated samples were prepared using EBs of energy 137, 183, 232, 400 keV,[12] and 2 MeV[11] in a fluence range of $(5.4–65)\times 10^{15}$ cm^{-2}, before fabrication of Schottky contacts to prevent damage for Schottky electrode during the EB irradiation process. DLTS measurements in a temperature range from 30 up to 370 K were performed. The temperature limitation prevents the migration of irradiation-induced defects.[9,12] The reverse bias was -5 V. The leakage current at the reverse bias was less than 3 nA, where accurate DLTS measurement can be obtained.[10] The filling pulse voltage was 0 V with a width t_p of more than 0.2 s. For this t_p condition, DLTS peaks observed in gamma-irradiated GaN at t_p less than 200 μs can be neglected.[9]

DLTS measurements showed that a DLTS peak was formed at low temperature by both gamma-ray and EB irradiation. From the Arrhenius plot, the energy level formed by gamma-ray irradiation was estimated to be $E_\mathrm{C} - 0.14$ eV, and the energy level formed by EB irradiation was estimated to be $E_\mathrm{C} - 0.13$ eV. The difference in the capture cross section of the electrons is less than one order of magnitude. The concentrations of these traps are proportional to the irradiation fluence. The PRs of these traps were obtained from the proportional slope. The concentrations of the traps formed by gamma-rays in different shielding materials were less than 10%, which is in good agreement with the NIEL calculation for gamma-rays. The experimental results for the energy levels and PRs of the traps formed by 1.25-MeV gamma-rays and EBs with various incident energy irradiation are summarized in Table I. The more detailed analysis for DLTS results of n-type GaN SBDs after gamma-rays[9] and EB irradiations[11,12] was showed in our previous reports. Table I also shows the PRs obtained in previous reports for evaluating traps at $E_\mathrm{C} - (0.12–0.20)$ eV formed by various energetic particles, such as electrons,[14,15] protons,[17] and α-rays.[18] The PRs that have not been previously reported were calculated from reported trap concentrations and incident fluences. The concentrations of the traps are considered to be uniform in the depth direction because the penetration depth of the incident energies in previous reports was much larger than the GaN epitaxial layer. Auret *et al.* reported that two trap levels were formed by PBs in n-type GaN at close energy levels (ER2: $E_\mathrm{C} - 0.16$ eV and ER3: $E_\mathrm{C} - 0.20$ eV) and suggested that the ER2 trap was hydrogen-related defects.[17] We took ER2 and ER3 into account for the NIEL comparison because ER2 may also be due to displacement-related defects. For evaluating the PRs of traps formed by gamma-ray irradiation, only the results of this study

TABLE I. Production rates of traps formed by various types of energetic particles at $E_\mathrm{C} - (0.12–020)$ eV.

Energetic particle	Incident energy	$E_\mathrm{C} - E_\mathrm{T}$/eV	PR/cm^{-1}	Reference
Gamma-rays	1.25 MeV	0.14	9.5×10^{-4}	This study[9]
Electrons	137 keV	0.13	1.6×10^{-3}	This study[12]
Electrons	183 keV	0.13	2.1×10^{-2}	This study[12]
Electrons	232 keV	0.13	0.04	This study[12]
Electrons	400 keV	0.13	0.09	This study[12]
Electrons	2 MeV	0.13	0.50	This study[11]
Electrons	1 MeV	0.18	0.2	Duc *et al.*[15]
Electrons	2 MeV	0.12	0.43	Fang *et al.*[14]
Protons	2 MeV	0.16	400	Auret *et al.*[17]
Protons	2 MeV	0.20	600	Auret *et al.*[17]
α-rays	5.4 MeV	0.20	3270	Auret *et al.*[18]

were used because the shielding environments for the previous studies were not clear,[36,37] and the nature and thickness of the shielding materials are important for calculating gamma-NIEL, as shown in Fig. 2.

Double logarithmic plots of the PRs of traps at $E_C - (0.12–0.20)$ eV for gamma-rays (Al shield), electrons, protons, and α-rays as a function of NIEL are shown in Fig. 3 as circle, squares, triangles, and a cross, respectively. The logarithmic PRs obtained from our experimental results and other previous reports show a linear correlation with the logarithmic NIEL. The slope of the fitting line in Fig. 3 is 1.0, indicating that the PRs of the traps are proportional to the NIEL in a range of about eight orders of magnitude. The correlation of PR with NIEL strongly indicates that traps at $E_C - (0.12–0.20)$ eV formed by various energetic particles have the same origin, namely, being generated by atomic displacements (V_N-related defects).

For compound materials, the NIEL of a selected atom can be calculated. If only the displacement of N in GaN contributes to the formation of the defects, the PRs will have a correlation with NIEL only for N. However, we found poor linearity for the correlation between the NIEL for N and PRs. As shown in Fig. 3, the PRs have a good linear correlation with the sum of the NIEL for both N and Ga, which suggests that Ga collision cascade may occur.

From a linear plot of PR vs NIEL, a proportional relationship was obtained as

$$\mathrm{PR}_{E_c-(0.12–0.20)\,\mathrm{eV}} = 1.8 \times 10^4\, {}^{\mathrm{g}}/_{\mathrm{cm^3\,MeV}} \cdot NIEL. \tag{3}$$

The error between the experimental results and this formula is within 30%. Using the coefficient from the formula, the PRs can also be shown in Fig. 1 (following the right axis). The equation and the obtained coefficient are useful for predicting the concentrations of the energy levels formed by various energetic particles with various incident energies and irradiation fluences.

There are several previous reports investigating the degradation of GaN-based devices due to various types of radiation, such as protons,[38,39] gamma-rays,[40,41] electrons,[42] and α-rays,[43] but these reports only include a qualitative discussion of the defects formed by the radiation. It is expected that traps formed by radiation cause degradation, such as decrease in luminous efficacies of LEDs due to decrease in carrier lifetime, decrease in energy conversion efficiencies of solar cells, increase in on-resistances, and decrease in break-down voltages and fluctuation of threshold voltages on power switching devices and high-frequency devices. Calculating PRs using NIEL enables the degradation of device characteristics to be simulated and compared for different incident particles or device structures.

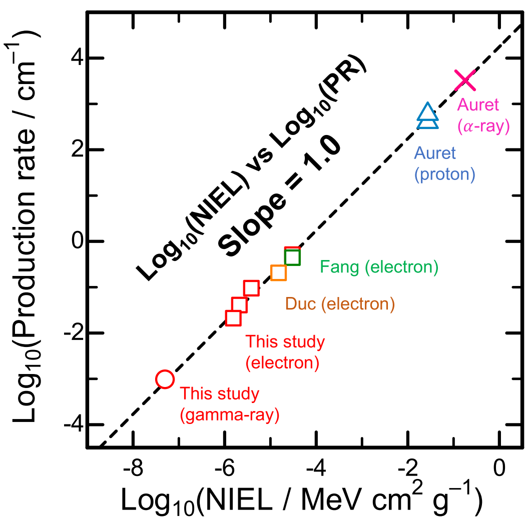

FIG. 3. PRs of electron traps at $E_C - (0.12–0.20)$ eV as a function of NIEL for electrons, protons, α-rays, and gamma-rays.

We demonstrated a clear correlation of NIEL with PR of an electron trap at $E_C - (0.12–0.20)$ eV formed by various types of energetic particles in GaN by a NIEL calculation and trap evaluation utilizing DLTS. The NIEL in GaN for electrons, protons, and α-rays was calculated, and the NIEL value for gamma-rays was calculated by simulating slowed-down spectra. To obtain the PRs of the electron trap, 1.25-MeV gamma-rays and EBs with energies from 137 keV to 2 MeV were irradiated on n-type GaN SBDs. In addition, we took the PRs of an electron trap with similar energy levels of $E_C - (0.12–0.20)$ eV from previous studies on electron, proton, and α-ray irradiation of GaN. The relationship between the PR values of the trap and NIEL is proportional in a range of eight orders of magnitude, indicating that the energy levels have the same origin, namely, being generated by atomic displacements (V_N-related defects). A clear correlation of NIEL with PRs of traps formed by various types of radiation has been obtained for GaN. The obtained relationship of Eq. (3) is useful for predicting the degradation of GaN-based devices caused by traps formed by various kinds of radiation.

This work was supported by the "MEXT-Program for Creation of Innovative Core Technology for Power Electronics" under Grant No. JPJ009777.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Keito Aoshima: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Writing – original draft (equal); Writing – review & editing (equal). **Masahiro Horita:** Data curation (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Resources (equal); Writing – review & editing (equal). **Jun Suda:** Funding acquisition (lead); Resources (equal); Supervision (equal); Validation (equal); Visualization (supporting); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1]C. Claeys and E. Simoen, *Radiation Effects in Advanced Semiconductor Materials and Devices* (Springer, Berlin, 2002), pp. 1–8.
[2]M. P. Khanal, B. Ozden, K. Kim, S. Uprety, V. Mirkhani, K. Yapabandara, A. C. Ahyi, and M. Park, J. Vac. Sci. Technol. B **35**, 03D107 (2017).

[3]M. A. Khan, A. Bhattarai, J. N. Kuznia, and D. T. Olson, Appl. Phys. Lett. **63**, 1214 (1993).
[4]T. Kachi, Jpn. J. Appl. Phys., Part 1 **53**, 100210 (2014).
[5]V. Cimalla, J. Pezoldt, and O. Ambacher, J. Phys. D **40**, S19 (2007).
[6]K. Trachenko, J. M. Pruneda, E. Artacho, and M. T. Dove, Phys. Rev. B **71**, 184104 (2005).
[7]J. Nord, K. Nordlund, and J. Keinonen, Phys. Rev. B **68**, 184108 (2003).
[8]D. V. Lang, J. Appl. Phys. **45**, 3023 (1974).
[9]K. Aoshima, K. Kanegae, M. Horita, and J. Suda, AIP Adv. **10**, 045023 (2020).
[10]K. Aoshima, M. Horita, and J. Suda, Aip Adv. **11**, 115124 (2021).
[11]M. Horita, T. Narita, T. Kachi, T. Uesugi, and J. Suda, paper presented at the International Workshop on Nitride Semiconductors, Kanazawa, Japan, 2018.
[12]M. Horita, T. Narita, T. Kachi, and J. Suda, Appl. Phys. Lett. **118**, 012106 (2021).
[13]S. A. Goodman, F. D. Auret, G. Myburg, M. J. Legodi, P. Gibart, and B. Beaumont, Mater. Sci. Eng., B **82**, 95 (2001).
[14]Z. Q. Fang, J. W. Hemsky, D. C. Look, and M. P. Mack, Appl. Phys. Lett. **72**, 448 (1998).
[15]T. T. Duc, G. Pozina, N. T. Son, E. Janzén, T. Ohshima, and C. Hemmingsson, Appl. Phys. Lett. **105**, 102103 (2014).
[16]A. Y. Polyakov, A. S. Usikov, B. Theys, N. B. Smirnov, A. V. Govorkov, F. Jomard, N. M. Shmidt, and W. V. Lundin, Solid·State Electron. **44**, 1971 (2000).
[17]F. D. Auret, S. A. Goodman, F. K. Koschnick, J. M. Spaeth, B. Beaumont, and P. Gibart, Appl. Phys. Lett. **74**, 407 (1999).
[18]F. D. Auret, S. A. Goodman, F. K. Koschnick, J. M. Spaeth, B. Beaumont, and P. Gibart, Appl. Phys. Lett. **73**, 3745 (1998).
[19]H. Iguchi, M. Horita, and J. Suda, Appl. Phys. Express **15**, 126501 (2022).
[20]E. E. Allam, C. Inguimbert, A. Meulenberg, A. Jorio, and I. Zorkani, J. Appl. Phys. **123**, 095703 (2018).
[21]A. L. Barry, A. J. Houdayer, P. F. Hinrichsen, W. G. Letourneau, and J. Vincent, IEEE Trans. Nucl. Sci. **42**, 2104 (1995).
[22]R. Radu, I. Pintilie, L. C. Nistor, E. Fretwurst, G. Lindstroem, and L. F. Makarenko, J. Appl. Phys. **117**, 164503 (2015).
[23]J. H. Warner, R. J. Walters, S. R. Messenger, G. P. Summers, S. M. Khanna, D. Estan, L. S. Erhardt, and A. Houdayer, IEEE Trans. Nucl. Sci. **51**, 2887 (2004).
[24]P. Hazdra and J. Vobecky, Phys. Status Solidi A **216**, 1900312 (2019).
[25]P. F. Hinrichsen, A. J. Houdayer, A. L. Barry, and J. Vincent, IEEE Trans. Nucl. Sci. **45**, 2808 (1998).
[26]S. M. Khanna, D. Estan, L. S. Erhardt, A. Houdayer, C. Carlone, A. Lonascut-Nedelcescu, S. R. Messenger, R. J. Walters, G. P. Summers, J. H. Warner, and I. Jun, IEEE Trans. Nucl. Sci. **51**, 2729 (2004).
[27]C. Leroy and P. G. Rancoita, *Principles of Radiation Interaction in Matter and Detection*, 4th ed. (World Scientific, 2016), pp. 477–567.
[28]S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand, F. Behner, L. Bellagamba, J. Boudreau, L. Broglia, A. Brunengo, H. Burkhardt, S. Chauvie, J. Chuma, R. Chytracek, G. Cooperman, G. Cosmo, P. Degtyarenko, A. Dell'Acqua, G. Depaola, D. Dietrich, R. Enami, A. Feliciello, C. Ferguson, H. Fesefeldt, G. Folger, F. Foppiano, A. Forti, S. Garelli, S. Giani, R. Giannitrapani, D. Gibin, J. J. Gómez Cadenas, I. Gonzalez, G. Gracia Abril, G. Greeniaus, W. Greiner, V. Grichine, A. Grossheim, S. Guatelli, P. Gumplinger, R. Hamatsu, K. Hashimoto, H. Hasui, A. Heikkinen, A. Howard, V. Ivanchenko, A. Johnson, F. W. Jones, J. Kallenbach, N. Kanaya, M. Kawabata, Y. Kawabata, M. Kawaguti, S. Kelner, P. Kent, A. Kimura, T. Kodama, R. Kokoulin, M. Kossov, H. Kurashige, E. Lamanna, T. Lampen, V. Lara, V. Lefebure, F. Lei, M. Liendl, W. Lockman, F. Longo, S. Magni, M. Maire, E. Medernach, K. Minamimoto, P. M. de Freitas, Y. Morita, K. Murakami, M. Nagamatu, R. Nartallo, P. Nieminen, T. Nishimura, K. Ohtsubo, M. Okamura, S. O'Neale, Y. Oohata, K. Paech, J. Perl, A. Pfeiffer, M. G. Pia, F. Ranjard, A. Rybin, S. Sadilov, E. D. Salvo, G. Santin, T. Sasaki, N. Savvas, Y. Sawada, S. Scherer, S. Seil, V. Sirotenko, D. Smith, N. Starkov, H. Stoecker, J. Sulkimo, M. Takahata, S. Tanaka, E. Tcherniaev, E. S. Tehrani, M. Tropeano, P. Truscott, H. Uno, L. Urban, P. Urban, M. Verderi, A. Walkden, W. Wander, H. Weber, J. P. Wellisch, T. Wenaus, D. C. Williams, D. Wright, T. Yamada, H. Yoshida, and D. Zschiesche, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[29]M. J. Boschini, P. G. Rancoita, and M. Tacconi, *SR-NIEL—7 Calculator: Screened Relativistic (SR) Treatment for Calculating the Displacement Damage and Nuclear Stopping Powers for Electrons, Protons, Light- and Heavy-Ions in Materials (Version 9.0)* (INFN Sez, Milano-Bicocca, Italy, 2004).
[30]J. Nord, K. Nordlund, J. Keinonen, and K. Albe, Nucl. Instrum. Methods Phys. Res., Sect. B **202**, 93 (2003).
[31]I. Jun, W. Kim, and R. Evans, IEEE Trans. Nucl. Sci. **56**, 3229 (2009).
[32]G. P. Summers, E. A. Burke, P. Shapiro, S. R. Messenger, and R. J. Walters, IEEE Trans. Nucl. Sci. **40**, 1372 (1993).
[33]D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).
[34]A. Akkerman, J. Barak, M. B. Chadwick, J. Levinson, M. Murat, and Y. Lifshitz, Radiat. Phys. Chem. **62**, 301 (2001).
[35]J. H. Hubbell, Int. J. Appl. Radiat. Isotopes **33**, 1269 (1982).
[36]N. M. Shmidt, D. V. Davydov, V. V. Emtsev, I. L. Krestnikov, A. A. Lebedev, W. V. Lundin, D. S. Poloskin, A. V. Sakharov, A. S. Usikov, and A. V. Osinsky, Phys. Status Solidi B **216**, 533 (1999).
[37]G. A. Umana-Membreno, J. A. Dell, G. Parish, B. D. Nener, L. Faraone, and U. K. Mishra, IEEE Trans. Electron Devices **50**, 2326 (2003).
[38]A. P. Karmarkar, B. Jun, D. M. Fleetwood, R. D. Schrimpf, R. A. Weller, B. D. White, L. J. Brillson, and U. K. Mishra, IEEE Trans. Nucl. Sci. **51**, 3801 (2004).
[39]X. W. Hu, A. P. Karmarkar, B. Jun, D. M. Fleetwood, R. D. Schrimpf, R. D. Geil, R. A. Weller, B. D. White, M. Bataiev, L. J. Brillson, and U. K. Mishra, IEEE Trans. Nucl. Sci. **50**, 1791 (2003).
[40]C. Schwarz, A. Yadav, M. Shatkhin, E. Flitsiyan, L. Chernyak, V. Kasiyan, L. Liu, Y. Y. Xi, F. Ren, S. J. Pearton, C. F. Lo, J. W. Johnson, and E. Danilova, Appl. Phys. Lett. **102**, 062102 (2013).
[41]A. Yadav, E. Flitsiyan, L. Chernyak, Y. H. Hwang, Y. L. Hsieh, L. Lei, F. Ren, S. J. Pearton, and I. Lubomirsky, Radiat. Eff. Defects Solids **170**, 377 (2015).
[42]S. J. Pearton, R. Deist, F. Ren, L. Liu, A. Y. Polyakov, and J. Kim, J. Vac. Sci. Technol. A **31**, 050801 (2013).
[43]F. Danesin, F. Zanon, S. Gerardin, F. Rampazzo, G. Meneghesso, E. Zanoni, and A. Paccagnella, Microelectron. Reliab. **46**, 1750 (2006).