Journal of Applied Physics

Reversible total ionizing dose effects in NiO/Ga_2O_3 heterojunction rectifiers

Cite as: J. Appl. Phys. **133**, 015702 (2023); https://doi.org/10.1063/5.0134823
Submitted: 22 November 2022 • Accepted: 13 December 2022 • Published Online: 03 January 2023

Jian-Sian Li, Chao-Ching Chiang, Xinyi Xia, et al.

Journal of Applied Physics ARTICLE scitation.org/journal/jap

Reversible total ionizing dose effects in NiO/Ga_2O_3 heterojunction rectifiers

Cite as: J. Appl. Phys. **133**, 015702 (2023); doi: 10.1063/5.0134823
Submitted: 22 November 2022 · Accepted: 13 December 2022 ·
Published Online: 3 January 2023

Jian-Sian Li,[1] Chao-Ching Chiang,[1] Xinyi Xia,[1] Sergei Stepanoff,[2] Aman Haque,[3] Douglas E. Wolfe,[2] Fan Ren,[1] and S. J. Pearton[4,a)]

AFFILIATIONS

[1]Department of Chemical Engineering, University of Florida, Gainesville, Florida 32606, USA
[2]Department of Materials Science & Engineering, Penn State University, University Park, Pennsylvania 16802, USA
[3]Department of Mechanical Engineering, Penn State University, University Park, Pennsylvania 16802, USA
[4]Department of Materials Science and Engineering, University of Florida, Gainesville, Florida 32606 USA

Note: This paper is part of the Special Topic on Radiation Effects in Materials.
[a)]**Author to whom correspondence should be addressed:** spear@mse.ufl.edu

ABSTRACT

NiO/Ga_2O_3 heterojunction rectifiers were exposed to 1 Mrad fluences of Co-60 γ-rays either with or without reverse biases. While there is a small component of Compton electrons (600 keV), generated via the interaction of 1.17 and 1.33 MeV gamma photons with the semiconductor, which in turn can lead to displacement damage, most of the energy is lost to ionization. The effect of the exposure to radiation is a 1000× reduction in forward current and a 100× increase in reverse current in the rectifiers, which is independent of whether the devices were biased during this step. The on–off ratio is also reduced by almost five orders of magnitude. There is a slight reduction in carrier concentration in the Ga_2O_3 drift region, with an effective carrier removal rate of <4 cm^{-1}. The changes in electrical characteristics are reversible by application of short forward current pulses during repeated measurement of the current–voltage characteristics at room temperature. There are no permanent total ionizing dose effects present in the rectifiers to 1 Mad fluences, which along with their resistance to displacement damage effects indicate that these devices may be well-suited to harsh terrestrial and space radiation applications if appropriate bias sequences are implemented to reverse the radiation-induced changes.

INTRODUCTION

There is increasing interest in ultra-wide bandgap semiconductors for their use in power electronic switching systems with improved efficiency and, hence, lower resistive losses.[1–5] There are also advantages in terms of operation at higher temperatures, higher breakdown voltages, and the ability to sustain larger and faster switching transients than Si devices. Examples of these potential applications include traction inverter and motor control systems, which are critical components in optimizing electric vehicles performance and maximizing the available driving range by reducing power losses and improving system efficiency. In addition, power switching transistors are needed for DC charging stations for electrical vehicles. Ultra-wide bandgap semiconductor devices, including Ga_2O_3, diamond, AlN, and BN, are targeted for >10 kV power electronics, providing the foundation for smart power grids and future 5G/6G wireless communications and radar systems. The strong atomic bonding and high defect recombination rates at room temperature are reasons why these materials also display strong resistance to radiation damage displacement effects and highlights their potential for operation in harsh space or terrestrial environments.

However, there is still much to understand in terms of the response of these materials to various radiation environments, including total ionizing dose conditions where ionization energy deposition dominates and single event upsets during heavy ion strikes.[6–10] For example, SiC power MOSFETs exhibit latent heavy ion damage to the gate oxide at drain to source bias voltages much lower than the rated breakdown voltages.[6–8]

There has been significant interest in heterojunction power rectifiers of NiO/Ga_2O_3 to overcome the lack of native p-type doping capability in Ga_2O_3, and promising results have been

reported.[11–26] However, the presence of the oxide rather than a conventional Schottky contact raises the question of the possible susceptibility of such devices to ionizing radiation, which can be conveniently studied using gamma rays.[27] Total ionizing dose (TID) testing using Co-60 γ sources remains the standard test method.[28]

Gamma rays interact with semiconductors by three mechanisms.[29] The photoelectric effect dominates for energies <1 MeV, while pair production dominates at >10 MeV. At the intermediate energies of Co-60 γ-rays, Compton scattering is the main energy loss mechanism. This can lead to secondary electrons produced by incident gammas, which are also able to displace lattice atoms.[29–31] The primary displacement defects created in Ga_2O_3 by gamma irradiation are Frenkel pairs, produced by these Compton electrons. The non-ionizing energy loss (NIEL) for gamma rays is much less than for ions, with only a few percent of the gamma photon flux creating secondary Compton electrons. In MOS-type devices, the passage of ionizing radiation through the oxide leads to changes in trapped and interface charges, which significantly affects device performance.[31–35] The e–h pair production, subsequent charge transport, and formation of interface and border traps in the insulating oxide is well-established as dominating the radiation response of Si MOS electronics.[31–35] However, we are using a highly conducting p-type oxide (NiO) to form a p–n heterojunction with Ga_2O_3, and little is known about charging and discharging processes in this system.

In this paper, we report on the response of NiO/Ga_2O_3 rectifiers to Co-60 gamma rays and show that there are no issues with charging within the NiO and that reductions in forward and reverse current after high doses of gamma rays can be reversed by biasing during resting of the devices. While introduction of trapped charges and their annihilation via carrier injection has been well known in Si-oxide structures for a long period,[31–35] there is much less known about the response to ionizing radiation of the type of highly conducting p-type oxides used here to form p–n heterojunctions with a newly emerging semiconductor, Ga_2O_3.

EXPERIMENTAL

The NiO layers were deposited by magnetron sputtering in a Kurt Lesker system at 3 mTorr working pressure and 150 W of 13.56 MHz power using two targets to achieve a deposition rate around 2 Å s^{-1}.[25] The O_2/Ar gas ratio was 1/10 or 1/3 producing polycrystalline films with a bandgap of 3.75 eV and a density of 5.6 g cm^{-3}. The device structure was a 10 μm thick epitaxial layer (2×10^{16} cm^{-3}) grown by halide vapor phase epitaxy (HVPE) on a (001) surface orientation n^+ β-Ga_2O_3 single crystal substrate (Novel Crystal Technology, Japan). The backside Ti/Au Ohmic contact was deposited by e-beam evaporation and annealed at 550 °C for 60 s under N_2. The carrier concentration in the NiO bilayer (10 nm/10 nm) structure was controlled by the Ar/O_2 ratio during sputtering at levels of 2×10^{18}–3×10^{19} cm^{-3}, with mobility <1 cm^2 V^{-1} s^{-1}. This structure was to optimize both breakdown voltage and contact resistance.[25] An Ni/Au contact metal (200–1000 μm diameter) was deposited onto the NiO layer after annealing at 300 °C under O_2 ambient. Figure 1 shows both (a) schematic of the device structure and (b) an optical image of the completed device.

The current–voltage (I–V) characteristics were recorded with a Tektronix 370-A curve tracer and a 371-B curve tracer, and an Agilent 4156C parameter analyzer was used for forward and reverse current and capacitance–voltage (C–V) measurements.

The samples were irradiated with Co-60 γ-rays in the Penn State Radiation Science and Engineering Center (RSEC) in a 1 MW Training, Research, Isotopes, and General Atomics (TRIGA) reactor core with associated dry-lead shield gamma testing facility. The National Institute of Standards and Technology (NIST)

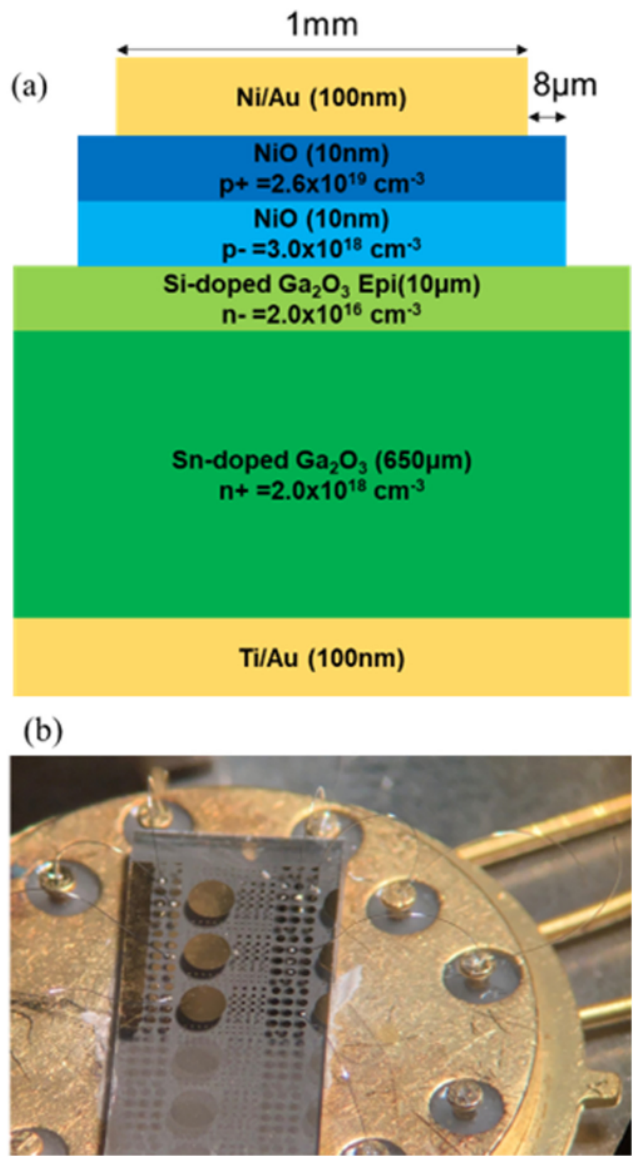

FIG. 1. (a) Schematic of the NiO/Ga_2O_3 heterojunction rectifier. (b) Optical microscope image of a wire-bonded completed device.

traceable certified dose rate ≈ 180 krad/h (±~10%), with the samples irradiated to 1 Mrad fluence (Φ), the number of particles per unit area. This is well beyond the existing generic requirement for radiation hardened military electronics of 300 krad (Si) but is equal to the "stretch" goal of 1 Mrad (Si).[35] ^{60}Co sources surround the samples during irradiation, and because of the way the sources are arranged, there is a region within the irradiator, where there is little variation in the dose rate, called the isodose region. As a result, the samples receive an isotropic gamma dose. The main 60 Co-60 gamma-photon lines are at 1.17 and 1.33 MeV. The effective gamma-ray fluence can be calculated from the total ionizing dose using the relation 1 rad (Si) = 2.0×10^9 photons/cm^2.[25] The TID is the energy lost to ionization/mass, which in turn is the linear energy loss (LET) × Φ. The LET is the energy deposited per unit path length due to ionization. No secondary irradiation is induced by irradiation of the Ga_2O_3 with Co-60 gamma rays, and therefore, the samples can be safely handled after the irradiation. The generation rate in NiO is ~10^{15} e–h pairs/Gy^1 cm^3 and ~2×10^{15} e–h pairs/Gy^1 cm^3 based on the reported threshold energies for pair creation.[36,37] The rectifiers were either unbiased or biased to 10 or 30 V during the radiation exposure of approximately 6 h.

RESULTS AND DISCUSSION

Figure 2 (a) shows the forward current density and associated on-state resistance R_{ON} for the unirradiated reference and devices irradiated either with or without bias. There are several points arising from these data. First, the forward current decreases by approximately three orders of magnitude after the irradiation. Second, this decrease is independent of bias. Normally, the application of bias has a strong influence on the radiation response and may occur at larger biases than we were able to apply in our experiments. Third, the on-resistance increases by three orders of magnitude as a result of irradiation. Figure 2 (b) shows that the forward current is fully restored by subsequent re-measurement of the I–V characteristics. This suggests that the initial changes are due to filling of existing traps and not due to creation of stable lattice defects. Notice that there was also no shift of the I–V characteristics, indicating that there are no additional charges trapped in the NiO.

Figure 3 shows the reverse I–V characteristics from the heterojunction rectifiers before and after gamma irradiation and then subsequent re-measurement of the forward I–V characteristics. Note that there is a two order of magnitude increase in reverse current as a result of the radiation exposure. However, this is fully restored by the process of putting the devices into a forward bias during re-measurement of the forward I–V characteristics. In our

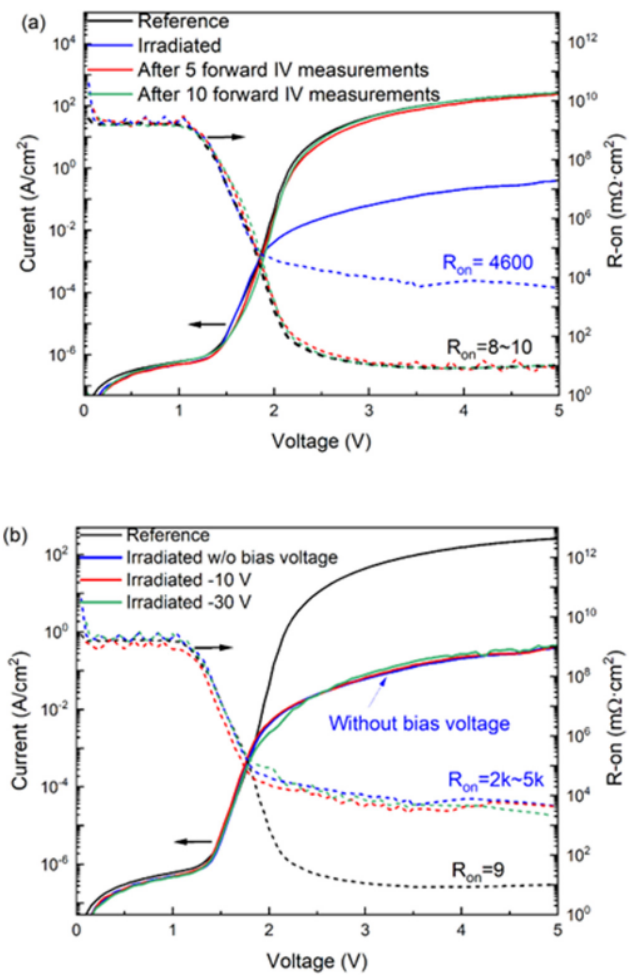

FIG. 2. (a) Forward current density and an on-state resistance before and after biased or unbiased irradiation with γ-radiation and (b) after subsequent repeated re-measurement of the forward I–V characteristics.

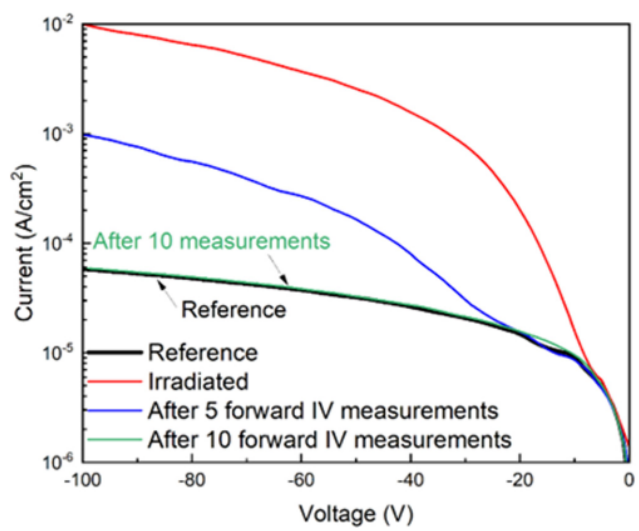

FIG. 3. Reverse I–V characteristics before and after biased irradiation with γ-radiation and after subsequent repeated re-measurement of the forward I–V characteristics.

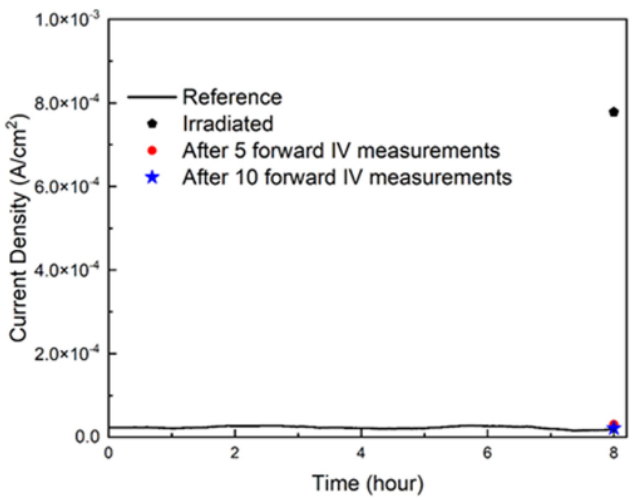

FIG. 4. Time dependence of reverse current density at a −30 V bias prior to irradiation, along with current values after irradiation for the same period.

devices, this full restoration of the initial reverse current occurs after ten re-measurements of the forward I–V characteristics.

We have to make clear that this is not due to any bias-stressing effects where traps may be created by the bias application during the period of the irradiation. Figure 4 shows the reverse current at a −30 V bias as a function of the bias application time for the reference sample. This is basically stable. However, the current measured at the end of the 6-h irradiation period for a companion device biased during the irradiation shows a large jump in reverse current. This excess current is removed by the re-measurement cycling.

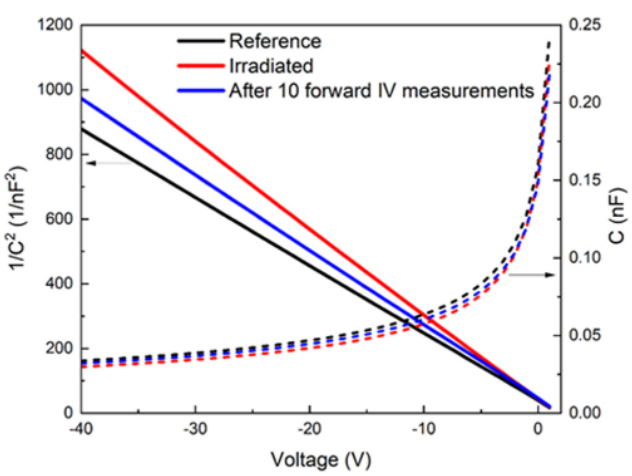

FIG. 5. C^{-2}–V characteristics before and after γ-irradiation and after subsequent repeated re-measurement of the forward I–V characteristics.

TABLE I. Changes in carrier concentration, depletion depth, and built-in voltage of $NiO/Ga_2O_{3=}$ rectifiers as a result of 1 Mrad Co-60 γ-irradiation.

	N_D (Ga_2O_3) (cm^{-3})	W_n (nm)	V_{bi} (V)
Reference	2.0×10^{16}	208	1.83
Irradiated	1.2×10^{16}	345	1.35
After ten runs	1.4×10^{16}	265	1.8

Figure 5 shows the capacitance–voltage (C–V) data, also plotted as $1/C^2$–V to obtain the carrier concentration in the Ga_2O_3 drift region. The carrier removal rates were extracted from[9]

$$R_c = \frac{n_{s0} - n_s}{\Phi},$$

where Φ is the photon fluence, n_{s0} is the initial carrier concentration, and n_s is the irradiated carrier concentration. The values were normalized to volume density to place them in units of cm^{-1}. The results are summarized in Table I, where it is seen that the carrier concentration shows a small reduction after irradiation, corresponding to a carrier removal rate of $<4\,cm^{-1}$ per gamma ray photon. This is consistent with previous reports for Co-60 γ-ray irradiation of Ga_2O_3 and cannot account for the large changes seen in forward and reverse current.[38,39] After the forward current re-measurement, part of the carrier concentration loss is restored.

The on–off ratio showed the same trends as the forward and reverse currents, as shown in Fig. 6. Since the reduction in forward current is much larger than that of the reverse current, the on–off ratio, measured for 2 V forward to the reverse bias noted on the x axis of Fig. 6, shows a large reduction. However, this reduction is

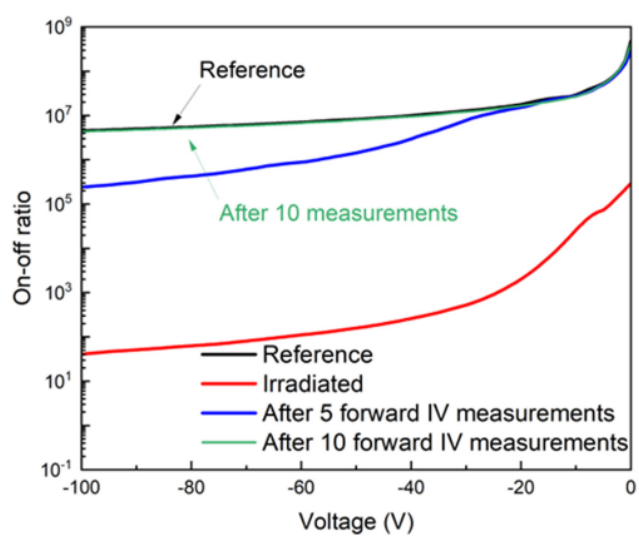

FIG. 6. On–off ratio measured from a 5 V forward bias to the reverse bias shown on the x axis before and after biased irradiation with γ-radiation and after subsequent repeated re-measurement of the forward I–V characteristics.

restored by the re-measurement of the forward I–V characteristics. Note that powering down a device can sometimes improve the radiation response, and we did not see a difference between zero bias and reverse biases up to −30 V. It will be interesting to test the devices at higher biases during irradiation.

What is the mechanism of the restoration of current in the rectifiers? The forward biasing injects holes from the NiO into the Ga_2O_3 and electrons into the NiO. These carriers can fill traps in the respective layer induced by the γ-radiation and restore the initial electrical properties.[40,41] Since the NiO is highly conducting, it is not expected that stored charge in that layer is a contributor. The minority carrier diffusion length in Ga_2O_3 is 330 nm for similar structures as used here,[42] consistent with the depletion lengths in Table I. The minority carrier lifetime is ∼215 ps, which is found to decrease with radiation exposure.[40,41] Modak *et al.*[42–45] reported that electron injection also increased the minority carrier lifetime by more than a factor of 2 in both n- and p-type Ga_2O_3 In that case, the mechanism was suggested to be non-equilibrium electron trapping on native defects (V_{Ga}) and a consequent increase in minority carrier lifetime in the conduction band of Ga_2O_3.[43] Before radiation-generated electrons leave the NiO, some fraction will recombine with holes and this fraction depends on the oxide electric field and the type and energy of incident radiation. While this fraction is unknown for NiO, it is <20% for γ-irradiation of SiO_2 at similar electric field values used here.[46] It is worth re-emphasizing that the effect of fixed or trapped charges in the highly conducting NiO is not an analogous situation to insulating oxides on Si MOS devices, which are sensitive to radiation-induced changes and in which the mechanisms are well-established.[47–55]

SUMMARY AND CONCLUSIONS

The damage created by gamma irradiation in NiO/Ga_2O_3 rectifiers can be recovered at room temperature by a non-thermal annealing scheme that can be easily implemented for devices. In its simplest form, this involves putting the device into a forward bias for a short period. Rasel *et al.*[55] have shown that an electron wind annealing process offers similar athermal annealing benefits in γ-irradiated GaN high electron mobility transistors. In that case, carriers were supplied by applying high current density electrical pulses with a low duty cycle. These types of athermal annealing approaches are intriguing for *in situ* regeneration of radiation-damaged wide and ultra-wide bandgap semiconductor power devices employed in harsh and remote environments. While the introduction of trapped charges and their annihilation via carrier injection is well understood in insulating oxide structures, more work is needed in these p–n heterojunctions involving conducting p-type oxides. Future work will include how dose rate, temperature, and biases relevant to device operation affect the response.

ACKNOWLEDGMENTS

The work at UF was performed as part of Interaction of Ionizing Radiation with Matter University Research Alliance (IIRM-URA), sponsored by the Department of the Defense, Defense Threat Reduction Agency under Award No. HDTRA1-20-2-0002. The content of the information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred. A.H. also acknowledges support from the U.S. National Science Foundation (ECCS No. 2015795). The work at UF was also supported by NSF DMR 1856662 (James Edgar).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Jian-Sian Li: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Chao-Ching Chiang:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Xinyi Xia:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **Sergei Stepanoff:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Aman Haque:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Writing – original draft (equal). **Douglas E. Wolfe:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Fan Ren:** Conceptualization (equal); Data curation (equal); Funding acquisition (equal); Investigation (equal); Writing – original draft (equal). **S. J. Pearton:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Methodology (equal); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

REFERENCES

[1] S. J. Pearton, J. Yang, P. H. Cary, F. Ren, J. Kim, M. J. Tadjer, and M. A. Mastro, Appl. Phys. Rev. **5**, 011301 (2018).
[2] K. Shenai, Proc. IEEE **107**, 2308 (2019).
[3] D. K. Shivani, A. Ghosh, and M. Kumar, Mater. Today Commun. **33**, 104244 (2022).
[4] J. Zhang, P. Dong, K. Dang, Y. Zhang, Q. Yan, H. Xiang, J. Su, Z. Liu, M. Si, J. Gao, M. Kong, H. Zhou, and Y. Hao, Nat. Commun. **13**, 3900 (2022).
[5] R. C. N. Pilawa-Podgurski, "Emerging circuit techniques to utilize widebandgap semiconductors in compact, lightweight, and efficient power converters," in *IEDM Technical Digest* (IEEE, 2021), pp. 5.6.1–5.6.4.
[6] J.-M. Lauenstein, M. C. Casey, R. L. Ladbury, H. S. Kim, A. M. Phan, and A. D. Topper, "Space radiation effects on SiC power device reliability," in *Proceedings of the IEEE International Reliability Physics Symposium (IRPS)* (IEEE, 2021), pp. 1–8.
[7] C. Abbate, G. Busatto, D. Tedesco, A. Sanseverino, F. Velardi, and J. Wyss, IEEE Trans. Electron Devices **66**, 4235 (2019).
[8] J.-B. Sauveplane, A. Dufour, E. Marcault, M. Orsatelli, G. Duran, J. Burky, B. Forgerit, F. Tilhac, and F.-X. Guerre, IEEE Trans. Nucl. Sci. **68**, 2488 (2021).
[9] X. Xia, J. S. Li, R. Sharma, F. Ren, M. A. J. Rasel, S. Stepanoff, N. Al Mamun, A. Haque, D. E. Wolfe, S. Modak, L. Chernyak, M. E. Law, A. Khachatrian, and S. J. Pearton, ECS J. Solid State Sci. Technol. **11**, 095001 (2022).

[10]S. J. Pearton, A. Aitkaliyeva, M. Xian, F. Ren, A. Khachatrian, A. Ildefonso, Z. Islam, M. A. J. Rasel, A. Haque, A. Y. Polyakov, and J. Kim, ECS J. Solid State Sci. Technol. **10**, 055008 (2021).
[11]J. Zhang, S. Han, M. Cui, X. Xu, W. Li, H. Xu, C. Jin, M. Gu, L. Chen, and K. H. L. Zhang, ACS Appl. Electron. Mater. **2**, 456 (2020).
[12]Y. Lv, Y. Wang, X. Fu, S. Dun, Z. Sun, H. Liu, X. Zhou, X. Song, K. Dang, S. Liang, J. Zhang, H. Zhou, Z. Feng, S. Cai, and Y. Hao, IEEE Trans. Power Electron. **36**, 6179 (2021).
[13]H. H. Gong, X. H. Chen, Y. Xu, F.-F. Ren, S. L. Gu, and J. D. Ye, Appl. Phys. Lett. **117**, 022104 (2020).
[14]X. Lu, X. Zhou, H. Jiang, K. W. Ng, Z. Chen, Y. Pei, K. May Lau, and G. Wang, IEEE Electron Dev. Lett. **41**, 449 (2020).
[15]C. Wang, H. Gong, W. Lei, Y. Cai, Z. Hu, S. Xu, Z. Liu, Q. Feng, H. Zhou, J. Ye, J. Zhang, R. Zhang, and Y. Hao, IEEE Electron Dev. Lett. **42**, 485 (2021).
[16]Q. Yan, H. Gong, J. Zhang, J. Ye, H. Zhou, Z. Liu, S. Xu, C. Wang, Z. Hu, Q. Feng, J. Ning, C. Zhang, P. Ma, R. Zhang, and Y. Hao, Appl. Phys. Lett. **118**, 122102 (2021).
[17]H. Gong, F. Zhou, W. Xu, X. Yu, Y. Xu, Y. Yang, F.-f. Ren, S. Gu, Y. Zheng, R. Zhang, H. Lu, and J. Ye, IEEE Trans. Power Electron. **36**, 12213 (2021).
[18]H. H. Gong, X. X. Yu, Y. Xu, X. H. Chen, Y. Kuang, Y. J. Lv, Y. Yang, F.-F. Ren, Z. H. Feng, S. L. Gu, Y. D. Zheng, R. Zhang, and J. D. Ye, Appl. Phys. Lett. **118**, 202102 (2021).
[19]W. Hao, Q. He, K. Zhou, G. Xu, W. Xiong, X. Zhou, G. Jian, C. Chen, X. Zhao, and S. Long, Appl. Phys. Lett. **118**, 043501 (2021).
[20]F. Zhou, H. Gong, W. Xu, X. Yu, Y. Xu, Y. Yang, F.-f. Ren, S. Gu, Y. Zheng, R. Zhang, J. Ye, and H. Lu, IEEE Trans. Power Electron. **37**, 1223 (2022).
[21]J. Zhang, P. Dong, K. Dang, Y. Zhang, Q. Yan, H. Xiang, J. Su, Z. Liu, M. Si, J. Gao, M. Kong, H. Zhou, and Y. Hao, Nat. Commun. **13**, 3900 (2022).
[22]Q. Yan, H. Gong, H. Zhou, J. Zhang, J. Ye, Z. Liu, C. Wang, X. Zheng, R. Zhang, and Y. Hao, Appl. Phys. Lett. **120**, 092106 (2022).
[23]Y. J. Lv, Y. G. Wang, X. C. Fu, S. B. Dun, Z. F. Sun, H. Y. Liu, X. Y. Zhou, X. B. Song, K. Dang, S. X. Liang, J. C. Zhang, H. Zhou, Z. H. Feng, S. J. Cai, and Y. Hao, IEEE Trans. Power Electron. **36**, 6179 (2021).
[24]Y. Wang, H. Gong, Y. Lv, X. Fu, S. Dun, T. Han, H. Liu, X. Zhou, S. Liang, J. Ye, R. Zhang, A. Bu, S. Cai, and Z. Feng, IEEE Trans. Power Electron. **37**, 3743 (2022).
[25]J.-S. Li, C.-C. Chiang, X. Xia, F. Ren, H. Kim, and S. J. Pearton, Appl. Phys. Lett. **121**, 042105 (2022).
[26]X. Xia, J. S. Li, C. C. Chiang, T. J. Yoo, F. Ren, H. Kim, and S. J. Pearton, J. Phys. D **55**, 385105 (2022).
[27]G. P. Summers, E. A. Burke, P. Shapiro, S. R. Messenger, and R. J. Walters, IEEE Trans. Nucl. Sci. **40**, 1372 (1993).
[28]See http://escies.org/escc-specs/published/22900.pdf for "Total Dose Steady-State Irradiation Test Method," European Space Components Coordination Basic Specification No. 22900 (2016).
[29]R. D. Evans, *The Atomic Nucleus* (Tata McGraw-Hill, Bombay, 1955).
[30]E. El Allam, C. Inguimbert, A. Meulenberg, A. Jorio, and I. Zorkani, J. Appl. Phys. **123**, 095703 (2018).
[31]D. M. Fleetwood, IEEE Trans. Nucl. Sci. **60**, 1706 (2013).
[32]T. R. Oldham and F. B. McLean, IEEE Trans. Nucl. Sci. **50**, 483 (2003).
[33]J. R. Schwank, M. R. Shaneyfelt, D. M. Fleetwood, J. A. Felix, P. E. Dodd, P. Pailet, and V. Ferlet-Cavrois, IEEE Trans. Nucl. Sci. **55**, 1833 (2008).
[34]G. C. Messenger and M. S. Ash, *The Effects of Radiation on Electronic Systems* (Van Nostrand Reinhold Co., New York, 1986).
[35]R. Baumann and K. Kruckmeyer, *Radiation Handbook for Electronics* (Texas Instruments, Dallas, TX, 2013); see https://www.ti.com/seclit/eb/sgzy002a/sgzy002a.pdf.
[36]E. B. Yakimov, A. Y. Polyakov, I. V. Shchemerov, N. B. Smirnov, A. A. Vasilev, P. S. Vergeles, E. E. Yakimov, A. V. Chernykh, F. Ren, and S. J. Pearton, Appl. Phys. Lett. **118**, 202106 (2021).
[37]J. A. Spencer, A. L. Mock, A. G. Jacobs, M. Schubert, Y. Zhang, and M. J. Tadjer, Appl. Phys. Rev. **9**, 011315 (2022).
[38]J. C. Yang, G. J. Koller, C. Fares, F. Ren, S. J. Pearton, J. Bae, and J. Kim, ECS J. Solid State Sci. Technol. **8**, Q3041 (2019).
[39]J. Lee, E. Flitsiyan, L. Chernyak, J. Yang, F. Ren, S. J. Pearton, B. Meyler, and Y. J. Salzman, Appl. Phys. Lett. **112**, 082104 (2018).
[40]A. Y. Polyakov, N. B. Smirnov, I. V. Shchemerov, S. J. Pearton, F. Ren, A. V. Chernykh, P. B. Lagov, and T. V. Kulevoy, APL Mater. **6**, 096102 (2018).
[41]S. Modak, L. Chernyak, S. Khodorov, I. Lubomirsky, A. Ruzin, M. Xian, F. Ren, and S. J. Pearton, ECS J. Solid State Sci. Technol. **9**, 045018 (2020).
[42]S. Modak, A. Schulte, C. Sartel, V. Sallet, Y. Dumont, E. Chikoidze, X. Xia, F. Ren, S. J. Pearton, A. Ruzin, and L. Chernyak, Appl. Phys. Lett. **120**, 233503 (2022).
[43]S. Modak, J. Lee, L. Chernyak, J. Yang, F. Ren, S. J. Pearton, S. Khodorov, and I. Lubomirsky, AIP Adv. **9**, 015127 (2019).
[44]S. Modak, L. Chernyak, S. Khodorov, I. Lubomirsky, J. Yang, F. Ren, and S. J. Pearton, ECS J. Solid State Sci. Technol. **8**, Q3050 (2019).
[45]S. Modak, L. Chernyak, M. H. Xian, F. Ren, S. J. Pearton, S. Khodorov, I. Lubomirsky, A. Ruzin, and Z. Dashevsky, J. Appl. Phys. **128**, 085702 (2020).
[46]F. B. McLean and T. R. Oldham, "Basic mechanisms of radiation effects in electronic materials and devices," Final report, September 1986–September 1987, n.p., USA, 1987; see https://www.osti.gov/biblio/5646360.
[47]D. M. Fleetwood, IEEE Trans. Nucl. Sci. **68**, 509 (2021).
[48]V. Ferlet-Cavrois, T. Colladant, P. Paillet, J. L. Leray, O. Musseau, J. R. Schwank, M. R. Shaneyfelt, J. L. Pelloie, and J. du Port de Poncharra, IEEE Trans. Nucl. Sci. **47**, 2183 (2000).
[49]P. S. Winokur, H. E. Boesch, Jr., J. M. McGarrity, and F. B. McLean, IEEE Trans. Nucl. Sci. **24**, 2113 (1977).
[50]P. S. Winokur, H. E. Boesch, Jr., J. M. McGarrity, and F. B. McLean, J. Appl. Phys. **50**, 3492 (1979).
[51]F. B. McLean, IEEE Trans. Nucl. Sci. **27**, 1651 (1980).
[52]S. T. Pantelides, S. N. Rashkeev, R. Buczko, D. M. Fleetwood, and R. D. Schrimpf, IEEE Trans. Nucl. Sci. **47**, 2262 (2000).
[53]S. N. Rashkeev, D. M. Fleetwood, R. D. Schrimpf, and S. T. Pantelides, IEEE Trans. Nucl. Sci. **48**, 2086 (2001).
[54]D. M. Fleetwood, Microelectron. Reliab. **42**, 523 (2002).
[55]M. A. J. Rasel, S. Stepanoff, A. Haque, D. E. Wolfe, F. Ren, and S. J. Pearton, ECS J. Solid State Sci. Technol. **11**, 075002 (2022).