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Mechanism of reverse gate leakage current reduction in AlGaN/GaN high-electron-mobility-transistor after 3-MeV proton irradiation

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ABSTRACT

A 3-MeV proton irradiation experiment was carried out on an AlGaN/GaN high-electron-mobility-transistor (HEMT). The results showed that the device's saturation drain current decreased, the threshold voltage drifted positively, and the maximum transconductance decreased after irradiation. Interestingly, the forward gate leakage current was almost unchanged, and the reverse gate leakage current was reduced by two orders of magnitude. We found that this experimental phenomenon can be well explained by the Poole–Frenkel emission model. Proton irradiation led to deeper defect energy levels and higher defect concentrations of the device. Deeper defect energy levels made it more difficult for electrons to be excited from the trap state into the conduction band. Thus, the reverse gate leakage current decreased. Higher defect concentrations led to degradation of the output and transfer curves of the device. The deep level transient spectroscopy characterization defect further proved the correctness of this model. The reduction in the reverse gate leakage current had a positive impact on AlGaN/GaN HEMT devices in high power or high frequency applications.

The third-generation semiconductor material GaN-based high-electron-mobility-transistors (HEMTs) are used in high-power and high-frequency applications such as power switches and RF amplifiers. This is due to their higher breakdown electric field, higher saturation electron drift velocity, and higher carrier mobility.[1,2] AlGaN/GaN HEMT devices are also widely used in aerospace applications due to their higher temperature resistance and stronger radiation resistance.[3–5] Protons are the most common particles in the space radiation environment, and proton irradiation usually leads to the degradations of the electric properties. Many proton radiation experiments have been carried out on AlGaN/GaN HEMT devices. Some of these experiments had reported that when the proton fluence reached the order of the 14th power, the reverse gate leakage current tended to reduce.[6–10]

Koehler *et al.* performed a 2-MeV proton irradiation experiment on AlGaN/GaN HEMTs.[11] When the cumulative fluence reached 6×10^{14} p/cm^2, the forward and reverse leakage current of the gate were reduced. Koehler found that the oxygen content on the surface of AlGaN had been improved after irradiation through the results of energy-dispersive x-ray spectroscopy (EDS). Koehler proposed that this interfacial oxide layer created a potential barrier for electrons, reducing the forward and reverse leakage current of the gate. This statement cannot explain how the forward gate leakage current is almost unchanged. Chen *et al.* performed a 1.8-MeV proton irradiation experiment on AlGaN/GaN HEMTs.[6] When the cumulative fluence reached 1×10^{14} p/cm^2, the forward gate leakage current hardly changed, and the reverse gate leakage current was reduced by 10%. Chen discovered this experimental phenomenon but did not give any explanations. Yue *et al.*[9] and Chen *et al.*[7] performed 3-MeV proton irradiation experiments on AlGaN/GaN HEMTs. When the cumulative fluence reached 6×10^{14} p/cm^2, the reverse gate leakage current was greatly reduced, and the forward gate leakage current was almost unchanged. Yue and Chen concluded that the internal defects of the devices increased after proton irradiation by measuring low frequency noise (LFN) and the gate delay. The increase in defects will lead to the degradation of the device. This cannot explain how the reverse gate leakage current had been reduced by two orders of magnitude.[7]

In this work, we investigated the effect of proton irradiation on the AlGaN/GaN HEMT device. The proton energy is 3-MeV, and the total fluence is 4×10^{14} p/cm^2. We report the Poole–Frenkel (PF) emission theory combined with the results of the deep level transient spectroscopy (DLTS) to explain the reduction in the reverse gate leakage current and the degradation of the output and the transfer curves. In this paper, we will describe in detail that protons irradiation changed the electrical performance of the device by changing the defect energy levels and the defect concentrations. This is a great significance for solving the problem of high gate leakage current of AlGaN/GaN HEMTs and improving the performance and reliability of the devices in the future.

The GaN buffer layer (2 μm), the AlN spacer layer (1 nm), and the $Al_{0.18}Ga_{0.82}N$ barrier layer (18 nm) were grown on a SiC substrate by metal organic chemical vapor deposition (MOCVD). The length and width of the Schottky contact gate formed by Mo/Pt/Au are 210 μm and 160 μm, respectively, and the spacing distance between the source and drain is 3.5 μm. The proton experiment was carried out at the Institute of Heavy Ion Physics, Peking University. The energy was 3-MeV, the proton flux was 1.48×10^{10} p/(cm^2 s), and the cumulative total fluence reached 4×10^{14} p/cm^2. The proton was normal incident into the devices during irradiation, and no bias was applied. The electrical properties were measured by Agilent B1500, and the trap characteristics were measured by DLTS before and after irradiation under the same test conditions. The protons have enough energy to pass completely through the active region of the device, as calculated by the stopping and range of ion in matter (SRIM).[12]

In order to understand the electrical performance changes before and after proton irradiation of the AlGaN/GaN HEMT device, the output curves, the transfer curves, and the gate leakage current curves were measured as shown in Fig. 1. The saturation drain current of the device decreased from 0.78 A to 0.51 A (a 35% reduction), and the slope of a linear region has also decreased [Fig. 1(a)]. The threshold voltage of the device has shifted forward 21% from −2.49 to −1.97 V [Fig. 1(b)]. From the output curve and transfer curve of the device, it can be seen that the performance of the device has deteriorated significantly. The forward gate leakage current was almost unchanged [Figs. 1(c) and 1(d)], which means that the Schottky barrier height had not changed.[13] The forward gate leakage current of Figs. 1(c) and 1(d) showed that proton irradiation had no effect on the Schottky gate. The reverse gate leakage current of the device has been reduced by two orders of magnitude, which is similar to the previous studies.[7,10] Analyzing the mechanism of the leakage current can provide an idea for suppressing the high reverse gate leakage current of AlGaN/GaN HEMT devices.

The Poole–Frenkel (PF) emission model, the thermionic emission (TE) model, the Fowler–Nordheim (FN) tunneling model, and the other trap-assisted tunneling (TAT) model are the most widely used models to explain the gate leakage mechanism of AlGaN/GaN HEMT devices.[11] The comparison among the value of the leakage

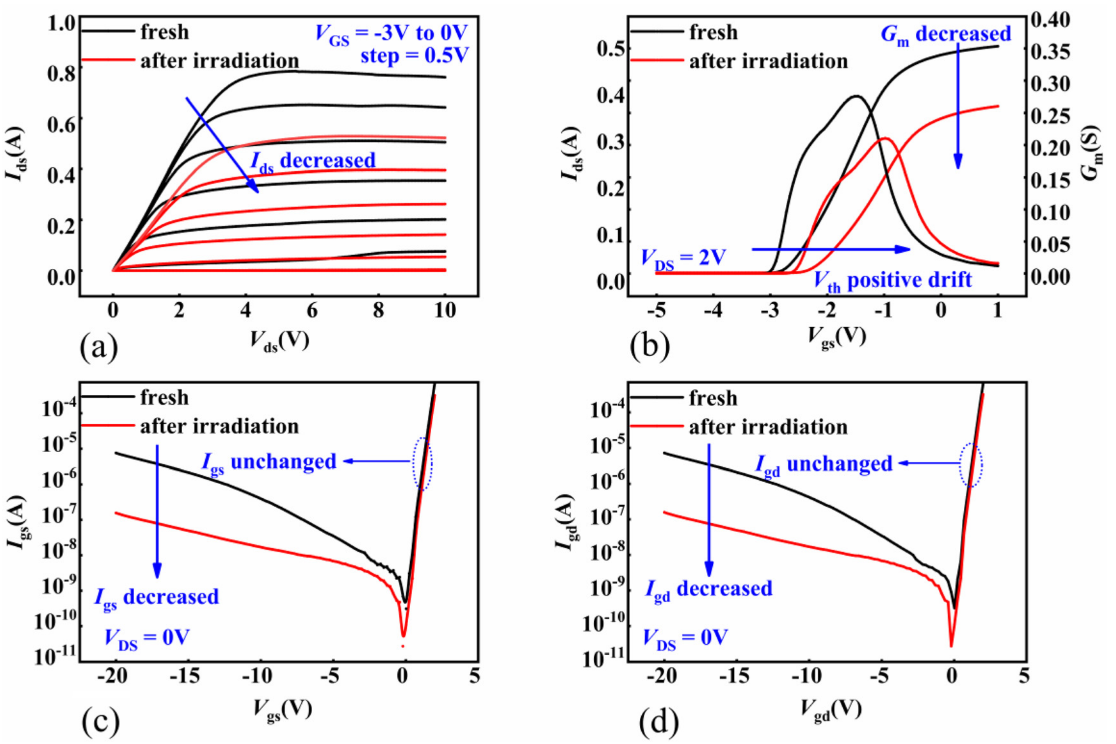

FIG. 1. (a) Current vs voltage curves before and after irradiation, (b) drain current, (c) gate-source current, and (d) gate-drain current characteristic curves before and after irradiation.

current predicted by the PF emission model, the TE model, and the FN tunneling model and the experimental results are shown in Fig. 2(a). It is shown that the value of the leakage current predicted by the TE model is significantly lower than that measured by its experimental results. The current value predicted by the FN tunneling model, which is closely related to voltage, is higher than the experimental results. The current value predicted by the PF emission model is basically consistent with the experimental results at low fields (-10 to 0 V). The deviation at high fields (-20 to -10 V) is since the FN tunneling effect starts to dominate at high fields. This is due to the AlGaN/GaN HEMTs devices itself. Its reverse gate leakage current at high fields is jointly caused by the PF emission model and the FN tunneling effect.[14] The FN tunneling is independent of proton irradiation and defect level. We will explain in detail later why the mechanism of reducing the reverse gate leakage current after proton irradiation is mainly PF emission, not FN tunneling.

The PF emission model points out that under the influence of the electric field strength, the energy band of the material will be bent. This phenomenon will reduce the defect energy level of the material. The reduction of the defect energy level would cause the electrons be excited from the trap state to the conduction band. The relationship between the current density (J_{PF}) and the electric field (E) for the PF emission model is shown below,

$$J_{PF} = \sigma_{PF} E \exp\left[\frac{-q\left(\varphi_B - \sqrt{(qE/\pi\varepsilon\varepsilon_0)}\right)}{kT}\right], \tag{1}$$

where σ_{PF} is the conductivity of the PF emission model, E is the electric field, φ_{B} is the emission height of the zero electric field barrier, ε_0 is the vacuum dielectric constant, and ε is the relative permittivity of GaN. Equation (1) can also be rearranged as[15]

$$\ln\left(J_{PF}/E\right) = A(T)\sqrt{E} + B(T). \tag{2}$$

From Eq. (2), it can be concluded that if the gate leakage mechanism is predicted by the PF emission model, then $\ln(J/E)$ and $\sqrt{E}$ satisfy the positive linear relationship. The electric field can be obtained by C–V curve integration,[16,17] and the relationship between the electric field (E) and voltage (V) is shown in the inset of Fig. 2(b). From Fig. 2(b), the $\ln(J/E)$ has a positive linear relationship with $\sqrt{E}$. Equation (2) can be simplified to the relationship between $\ln(I/V)$ and $\sqrt{V}$,[18] and it satisfies the positive correlation [Fig. 3(a)]. Therefore, the PF emission model can explain the gate leakage current of AlGaN/GaN HEMT devices. The experiment results are in good agreement with the PF emission model.

The PF emission model points out that for GaN-based HEMT devices, the probability of electrons moving through drift and diffusion is reduced due to the existence of traps. The trap capture and release of electrons become the primary process. As mentioned above, the bending of the energy band of the material results in the reduction of the defect energy level, so the electrons easily have enough energy to be excited from the trap state to the conduction band. After the proton irradiation, the energy level of the defect became deeper. Therefore, it is more difficult for the electrons to be excited from the trap state to the conduction band and the reverse gate leakage current reduced. After proton irradiation, the increase in the concentration of the defects is the reason for the degradation of the output and transfer curves. The above assumption was also verified by DLTS results. The peak of DLTS reflected the information of defect energy level and defect concentration. The point of the peak H1 increased from 320 K before irradiation to 380 K after irradiation [Fig. 3(b)], meaning that a higher temperature is required to excite the defects of the device. In other words, the defect energy level became deeper after irradiation. The defect energy level changed from 0.691 ± 0.02 to 0.876 ± 0.03 eV, and the defect concentration also increased from 1.68×10^{15} to 5.05×10^{15} cm^{-3}. The energy band graph of the AlGaN/GaN HEMT device before and after proton irradiation is shown in Fig. 4. The parameter data in the figure were obtained from the test results of DLTS. The energy level of the defects is reduced by 0.185 ± 0.05 eV, so electrons in the trap state cannot be excited to the conduction band completely.

The DLTS results measured in this paper before irradiation are very similar to the GaN intrinsic defect energy level of 670 ± 20 meV.[19] Reference 19 reported that the defect types are due to nitrogen

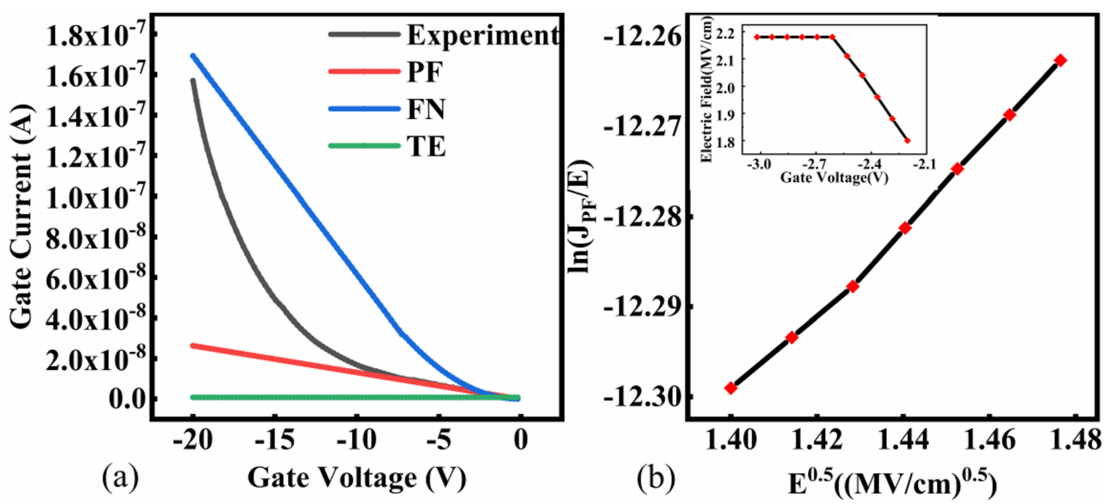

FIG. 2. (a) Comparison of the gate current after proton irradiation vs gate voltage predicted by the PF, TE, and FN models and the comparison of experimental data after proton irradiation and (b) ln (J_{PF}/E) vs $E^{0.5}$ relationship curve. Inset: E vs V curve.

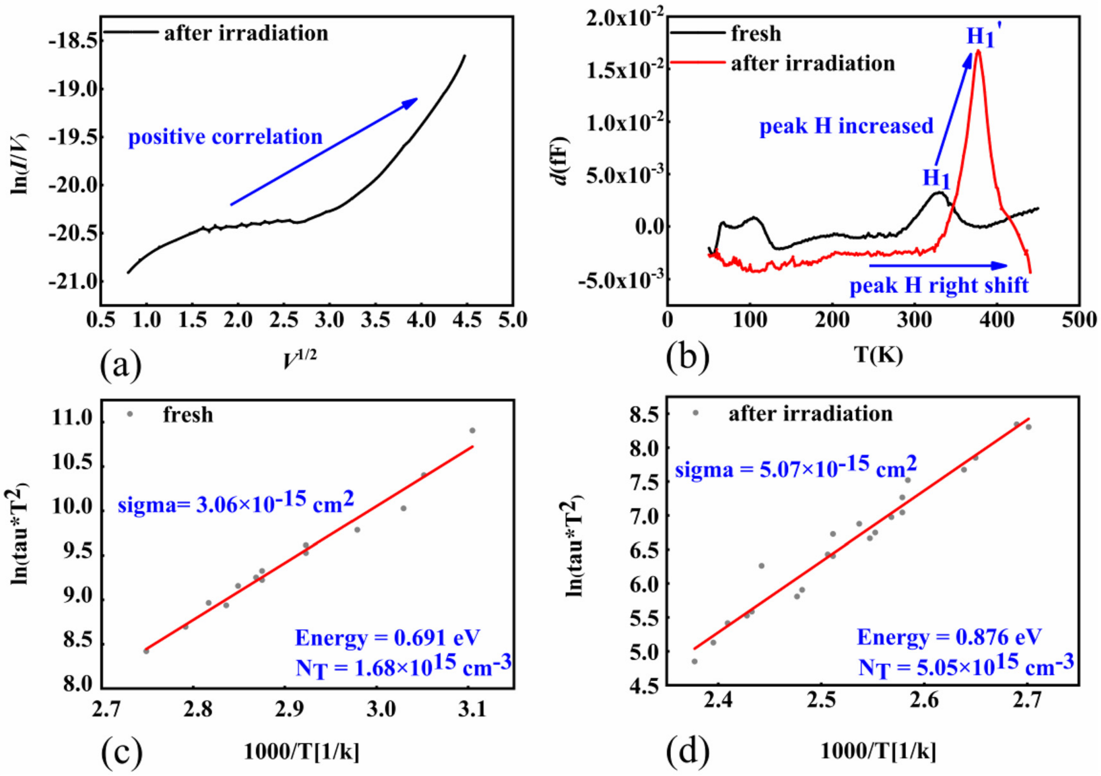

FIG. 3. (a) ln(I/V) vs $V^{1/2}$ relationship curve, (b) C-DLTS spectra test results before and after irradiation, and (c) before and (d) after irradiation Arrhenius plots determined from the peak tested by C-DLTS.

interstitial. The DLTS results measured in this paper after irradiation are also close to the defect energy level of 0.85 eV in Ref. 20. Reference 20 reported that the irradiation produced nitrogen interstitial type defects near this energy level. After the AlGaN/GaN HEMT device was irradiated by protons, the protons changed the nitrogen interstitial defect at the defect energy level (about 0.691 eV) before irradiation. Protons shift excess nitrogen atoms to deeper energy level (about 0.876 eV), resulting in new nitrogen interstitial defects. Proton irradiation caused defects near the two-dimensional electron gas because of the concentration of two-dimensional electron gas changed and near the AlGaN layer due to the defect energy level changed.

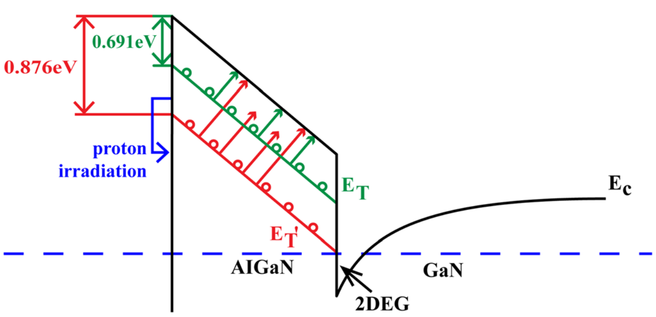

FIG. 4. AlGaN/GaN HEMT schematic band diagram before and after proton irradiation.

The pre-irradiation $J_{PF\,(pre)}$ predicted by the PF model divided by the post-irradiation $J_{PF\,(post)}$ predicted by the PF model is as follows:

$$\frac{J_{PF(pre)}}{J_{PF(post)}} = \frac{E_{pre}}{E_{post}} \times \exp\left\{\frac{q}{kT}\left[(\varphi_{post} - \varphi_{pre}) + \left(\sqrt{\frac{q}{\pi\varepsilon_i}}\left(\sqrt{E_{pre}} - \sqrt{E_{post}}\right)\right)\right]\right\}, \tag{3}$$

where $q\varphi_{post}$ is 0.876 ± 0.03 eV, $q\varphi_{pre}$ is 0.691 ± 0.02 eV, k is Boltzmann's constant, and T is the room temperature 300 K [the test temperature of Figs. 1(c) and 1(d)]. Its calculation result is

$$\frac{J_{PF(pre)}}{J_{PF(post)}} \approx 300. \tag{4}$$

The results show that the reverse gate leakage current decreased by about two orders of magnitude after proton irradiation, and the results are consistent with Figs. 1(c) and 1(d).

The relationship between the current density (J_{FN}) and the electric field (E) for the FN tunneling model is shown below,[15]

$$J_{FN} = AE^2 \exp\left[-\frac{\frac{8\pi\sqrt{2m_n^*(q\varphi_{eff})^3}}{3qh}}{E}\right]. \tag{5}$$

It can be seen from Eqs. (1) and (5) that the PF emission model is related to the electric field and defect energy level, and the electric field had a great impact on the FN tunneling model. The electric field is obtained by calculating the concentration of a two-dimensional electron gas (2DEG),[15,16] and the defect concentration changed the 2DEG concentration. From Eq. (3), the change in the defect energy level had a greater influence on the reduction of the reverse gate leakage current than the change in the defect concentration. Therefore, the reduction in the reverse gate leakage current by two orders of magnitude after proton irradiation is mainly caused by the deepening of the defect energy level.

The AlGaN/GaN HEMT device was subjected to a fluence of 4×10^{14} p/cm^2 3-MeV protons at room temperature. The results showed that the forward gate leakage current was almost unchanged, meaning the height of the Schottky barrier was unchanged, and the reverse gate leakage current was reduced by two orders of magnitude. The leakage mechanism was analyzed through the theory of the Poole–Frenkel emission model and the test results of deep level transient spectroscopy. After proton irradiation, the defect energy level of the device became deeper. The electrons did not have enough energy to be excited from the trap state to the conduction band. Therefore, the reverse gate leakage current reduced.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Changhao Sun: Conceptualization (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Xiangli Zhong:** Conceptualization (equal); Supervision (equal); Writing – review and editing (equal). **Chao Peng:** Supervision (equal); Writing – review and editing (equal). **Zhangang Zhang:** Supervision (equal). **Jinbin Wang:** Supervision (equal). **Shaozhong Yue:** Supervision (equal). **Hong Zhang:** Supervision (equal). **Ziwen Chen:** Supervision (equal). **Xiaoping Ouyang:** Supervision (equal). **Zhifeng Lei:** Resources (equal); Supervision (equal); Writing – review and editing (equal).

DATA AVAILABILITY

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

REFERENCES

[1] N. Ramanan, B. Lee, and V. Misra, IEEE Trans. Electron Devices **62**, 546–553 (2015).

[2] B. D. Weaver, P. A. Martin, J. B. Boos, and C. D. Cress, IEEE Trans. Nucl. Sci. **59**, 3077–3080 (2012).

[3] J. Marek, L. Stuchlikova, M. Jagelka, A. Chvala, P. Pribytny, M. Donoval, and D. Donoval, in *International Conference on Advanced Semiconductor Devices and Microsystems (ASDAM)* (IEEE, 2017), pp. 173–176.

[4] R. Jiang, E. X. Zhang, M. W. McCurdy, J. Chen, X. Shen, P. Wang, D. M. Fleetwood, R. D. Schrimpf, S. W. Kaun, E. C. H. Kyle, J. S. Speck, and S. T. Pantelides, IEEE Trans. Nucl. Sci. **64**, 218–225 (2017).

[5] Z. Zhang, A. R. Arehart, E. Cinkilic, J. Chen, E. X. Zhang, D. M. Fleetwood, R. D. Schrimpf, B. McSkimming, J. S. Speck, and S. A. Ringel, Appl. Phys. Lett. **103**, 042102 (2013).

[6] J. Chen, Y. S. Puzyrev, C. X. Zhang, E. X. Zhang, M. W. McCurdy, D. M. Fleetwood, R. D. Schrimpf, S. T. Pantelides, S. W. Kaun, E. C. H. Kyle, and J. S. Speck, IEEE Trans. Nucl. Sci. **60**, 4080–4086 (2013).

[7] Z. W. Chen, S. Z. Yue, J. B. Wang, Z. G. Zhang, Y. M. Huang, L. Wang, C. Peng, X. L. Zhong, and Z. F. Lei, IEEE Trans. Device Mater. Reliab. **21**, 297–302 (2021).

[8] B. D. White, M. Bataiev, S. H. Goss, X. Hu, A. Karmarkar, D. M. Fleetwood, R. D. Schrimpf, W. J. Schaff, and L. J. Brillson, IEEE Trans. Nucl. Sci. **50**, 1934–1941 (2003).

[9] S. Z. Yue, Z. F. Lei, C. Peng, X. L. Zhong, J. B. Wang, Z. G. Zhang, Y. F. En, Y. H. Wang, and L. Hu, IEEE Trans. Nucl. Sci. **67**, 1339–1344 (2020).

[10] Z. W. Chen, S. Y. Yue, C. Peng, Z. G. Zhang, C. Liu, L. Wang, Y. M. Huang, Y. Huang, Y. J. He, X. L. Zhong, and Z. F. Lei, IEEE Trans. Nucl. Sci. **68**, 118–123 (2021).

[11] A. D. Koehler, P. Specht, T. J. Anderson, B. D. Weaver, J. D. Greenlee, M. J. Tadjer, M. Porter, M. Wade, O. C. Dubon, K. D. Hobart, T. R. Weatherford, and F. J. Kub, IEEE Electron Device Lett. **35**, 1194–1196 (2014).

[12] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, Nucl. Instrum. Methods Phys. Res., Sect. B **268**, 1818–1823 (2010).

[13] J. C. Petrosky, J. W. McClory, T. E. Gray, and T. A. Uhlman, IEEE Trans. Nucl. Sci. **56**, 2905–2909 (2009).

[14] S. Turuvekere, D. S. Rawal, A. DasGupta, and N. DasGupta, IEEE Trans. Electron Devices **61**, 4291–4294 (2014).

[15] S. Turuvekere, N. Karumuri, A. A. Rahman, A. Bhattacharya, A. DasGupta, and N. DasGupta, IEEE Trans. Electron Devices **60**, 3157–3165 (2013).

[16] H. Zhang, E. J. Miller, and E. T. Yu, J. Appl. Phys. **99**, 023703 (2006).

[17] D. W. Yan, H. Lu, D. S. Cao, D. J. Chen, R. Zhang, and Y. D. Zheng, Appl. Phys. Lett. **97**, 153503 (2010).

[18] C. Ren, H. Yang, D. D. Han, J. F. Kang, X. Y. Liu, and R. Q. Han, Chin. J. Semicond. **24**, 1109–1114 (2003).

[19] D. Haase, M. Schmid, W. Kurner, A. Dornen, V. Harle, F. Scholz, M. Bukard, and H. Schweizer, Appl. Phys. Lett. **69**, 2525 (1996).

[20] Z. Q. Fang, L. Polenta, J. W. Hemsky, and D. C. Look, in *IEEE International Semiconducting and Insulating Materials Conference* (IEEE, 2000), pp. 35–42.