



Article

Research on the Synergistic Effect of Total Ionization and Displacement Dose in GaN HEMT Using Neutron and Gamma-Ray Irradiation

Rui Chen ^{1,2,*} , Yanan Liang ¹, Jianwei Han ^{1,2}, Qihong Lu ³, Qian Chen ¹, Ziyu Wang ¹, Hao Wang ¹, Xuan Wang ¹ and Runjie Yuan ¹

¹ National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China; liangyanan@nssc.ac.cn (Y.L.); hanjw@nssc.ac.cn (J.H.); chenqian16@mails.ucas.ac.cn (Q.C.); wangziyu211@mails.ucas.ac.cn (Z.W.); wanghao21c@mails.ucas.ac.cn (H.W.); wangxuan171@mails.ucas.ac.cn (X.W.); yuanrunjie20@mails.ucas.ac.cn (R.Y.)

² Institute of Astronomy and Space, University of Chinese Academy of Sciences, Beijing 101408, China

³ School of Physical Science and Technology, Yangzhou University, Yangzhou 225000, China; yzqlhaimenghuan@163.com

* Correspondence: chenrui2010@nssc.ac.cn

Abstract: This paper studies the synergistic effect of total ionizing dose (TID) and displacement damage dose (DDD) in enhancement-mode GaN high electron mobility transistor (HEMT) based on the p-GaN gate and cascode structure using neutron and ⁶⁰Co gamma-ray irradiation. The results show that when the accumulated gamma-ray doses are up to 800k rad(Si), the leakage-current degradations of the two types of GaN HEMTs with 14 MeV neutron irradiation of 1.3×10^{12} n/cm² and 3×10^{12} n/cm² exhibit a lower degradation than the sum of the two separated effects. However, the threshold voltage shifts of the cascode structure GaN HEMT show a higher degradation when exposed to both TID and DDD effects. Moreover, the failure mechanisms of the synergistic effect in GaN HEMT are investigated using the scanning electron microscopy technique. It is shown that for the p-GaNHEMT, the increase in channel resistance and the degradation of two-dimensional electron gas mobility caused by neutron irradiation suppresses the increase in the TID leakage current. For the cascode structure HEMT, the neutron radiation-generated defects in the oxide layer of the metal-oxide-semiconductor field-effect transistor might capture holes induced by gamma-ray irradiation, resulting in a further increase in the number of trapped charges in the oxide layer.

Keywords: displacement damage effect; total ionizing dose effect; gamma-ray; neutron; gallium nitride high electron mobility transistor



Citation: Chen, R.; Liang, Y.; Han, J.; Lu, Q.; Chen, Q.; Wang, Z.; Wang, H.; Wang, X.; Yuan, R. Research on the Synergistic Effect of Total Ionization and Displacement Dose in GaN HEMT Using Neutron and Gamma-Ray Irradiation.

Nanomaterials **2022**, *12*, 2126. <https://doi.org/10.3390/nano12132126>

Received: 13 May 2022

Accepted: 15 June 2022

Published: 21 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

As the representative of the wide bandgap semiconductor devices, the gallium nitride high-electron-mobility transistor (GaN HEMT) has excellent electrical performance, high-temperature resistance, high power, and resistance to extreme radiation environments, which could meet the needs of new-generation spacecraft energy systems [1–4]. When a nuclear-powered spacecraft works in space, in addition to radiation damage caused by energetic particles, the comprehensive radiation environment with neutrons and gamma rays could also lead to performance degradation or even device failure of electronic systems by displacement damage effects (DDD) and total dose effects (TID) [5–9]. According to the reports [10,11], at a distance of 5.3 m from the 461 MW nuclear reactor core, normalized by the power, the neutron flux with an energy greater than 3 MeV is 2.13×10^8 n·cm⁻²·s⁻¹·MW and an energy smaller than 0.4 MeV is 9.84×10^8 n·cm⁻²·s⁻¹·MW. Meanwhile, the gamma-ray dose rate is 0.08 Sv·s⁻¹·MW. At present, the TID and DDD effects of GaN HEMT have been, respectively, studied using neutron and gamma-ray radiation. For the TID case, it

involves the radiation characterization, failure mechanism, and mitigation design, while most DDD studies only focus on the radiation appearances under neutron and proton experiments. Moreover, some previous works show that the TID effect could be influenced by neutron radiation in bipolar transistors [8]. However, it is a pity that the synergistic effect of DDD and TID in GaN HEMT has not been reported so far. This is a challenge to evaluate the reliability of the electronic system in a comprehensive radiation environment involving neutrons and gamma-rays.

In this paper, the DDD and TID irradiation experiments are carried out with the 14 MeV neutron high-voltage multiplier and ^{60}Co gamma-ray successively. The experiment devices are the enhancement mode GaN HEMT based on the p-GaN gate and the cascode structure. The characteristics of the TID effect under neutron irradiation are studied and the failure mechanisms of the synergistic effect of DDD and TID in the GaN HEMT are revealed.

2. Experimental Setup

The DDD experiments of the GaN HEMT based on the p-GaN gate and the cascode structure were carried out by the 14 MeV neutron high-voltage multiplier at the China Institute of Atomic Energy. For p-GaN gate, GaN HEMT radiation, the neutron flux, and fluence were $5 \times 10^7 \text{ n/cm}^2/\text{s}$ and $3 \times 10^{12} \text{ n/cm}^2$, respectively. For the cascode structure GaN HEMT case, a flux of $2.6 \times 10^7 \text{ n/cm}^2/\text{s}$ and fluence of $1.3 \times 10^{12} \text{ n/cm}^2$ were adopted. The TID experiments of the GaN HEMT based on the p-GaN gate and the cascode structure were carried out using the ^{60}Co gamma-ray source at Peking University, China. The dose rate was 100 rad(Si)/s in the experiments. The TID characteristics of the GaN HEMT were tested online at 50k rad(Si) , 200k rad(Si) , 500k rad(Si) , and 800k rad(Si) , respectively. Then, 168-hour annealing at room temperature was performed after total dose irradiation. The experimental setup of the DDD and TID test is shown in Figure 1.



Figure 1. The experimental setup of (a) DDD and (b) TID test.

The commercially available E-mode GaN HEMTs with p-GaN gate and cascode structure was adopted in the DDD and TID testing. The device parameters are shown in Table 1. As shown in Figure 2, the test circuit refers to the MIL-STD-750D. Keithley 2470 and 2450 source measurement unit (SMU) are connected to the drain-source and gate-source terminal of the device through resistance and capacitance, respectively, which provide drain-source voltage (V_{ds}) and gate-source voltage (V_{gs}). Additionally, the current-voltage and transfer curve characterization were also obtained by them. The GaN HEMTs were biased on off-state ($V_{ds} = V_{gs} = 0 \text{ V}$) and on-state ($V_{ds} = 1 \text{ V}$, $V_{gs} = 2.6 \text{ V}$) during irradiation, respectively.

Table 1. Parameters of the device.

	Type	BV	Ron	Manufacturer
GS0650111L	P-type gate	650 V	150 mΩ	GaN Systems
TP90H180PS	Cascode	900 V	205 mΩ	Transphorm

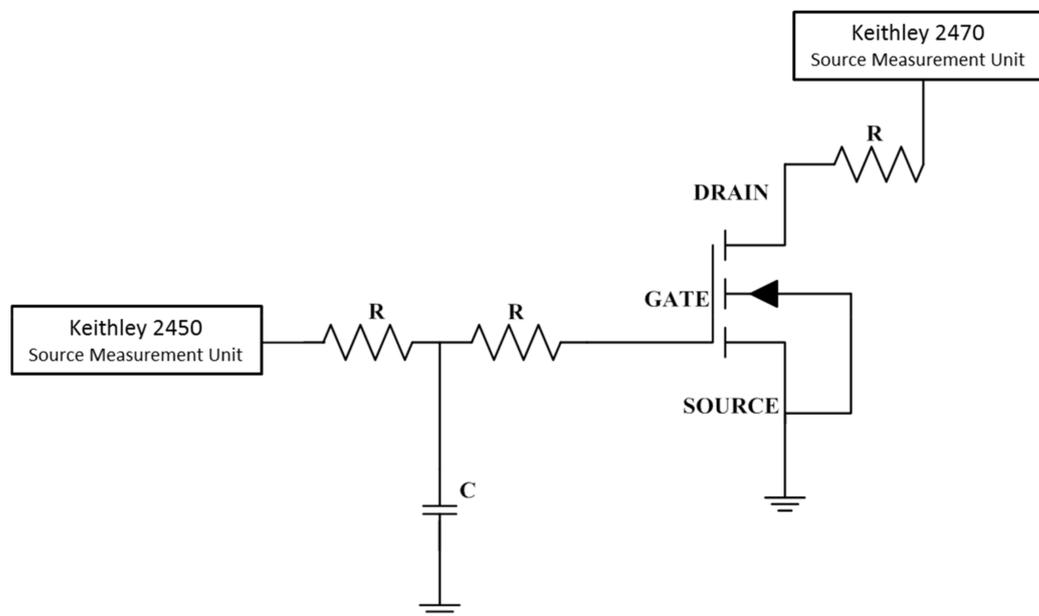


Figure 2. The schematic diagram of the DDD and TID test circuit.

3. Experimental Results

3.1. Neutron Irradiation

The relationships between leakage current variation and neutron irradiation fluence of TP90H180PS and GS0650111L are shown in Figure 3a,b. The leakage currents of TP90H180PS and GS0650111L before irradiation are 1.6 μA and 200 nA, respectively. When the neutron irradiation fluence accumulates to 1.3×10^{12} n/cm² and 3×10^{12} n/cm², respectively, the leakage current of the two-type devices increases slightly with neutron irradiation. The leakage current variations of the two-type devices under on-state radiation are 3.2×10^{-7} A and 1.5×10^{-8} A and under off-state radiation are 2.8×10^{-7} A and 9×10^{-8} A, respectively.

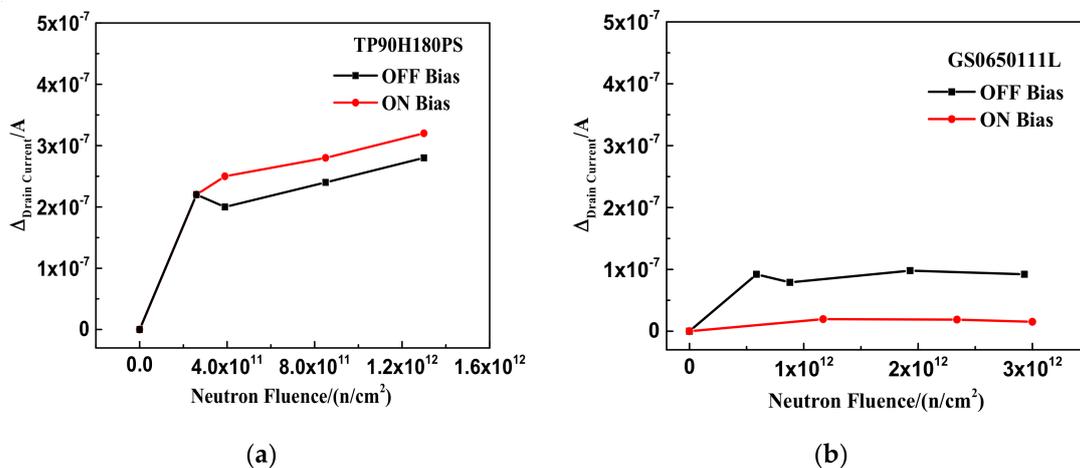


Figure 3. The relationship between the leakage current variations of the device and the neutron irradiation under the on-state and off-state: (a) TP90H180PS and (b) GS0650111L.

Figure 4 shows the threshold voltage shifts as the function of neutron irradiation influence for the GaN HEMT based on the p-GaN gate and the cascode structure. It is shown that in Figure 4a the threshold voltage offsets of the TP90H180PS negatively shift about 0.1 V under on- and off-bias with neutron fluence of 1.3×10^{12} n/cm². In addition, as shown in Figure 4b, the threshold voltage offsets of the GS0650111L also negatively shift under on- and off-bias with neutron fluence of 3×10^{12} n/cm². The maximum threshold voltage shifts are approximately -0.25 V under on-bias and -0.2 V under off-bias, respectively.

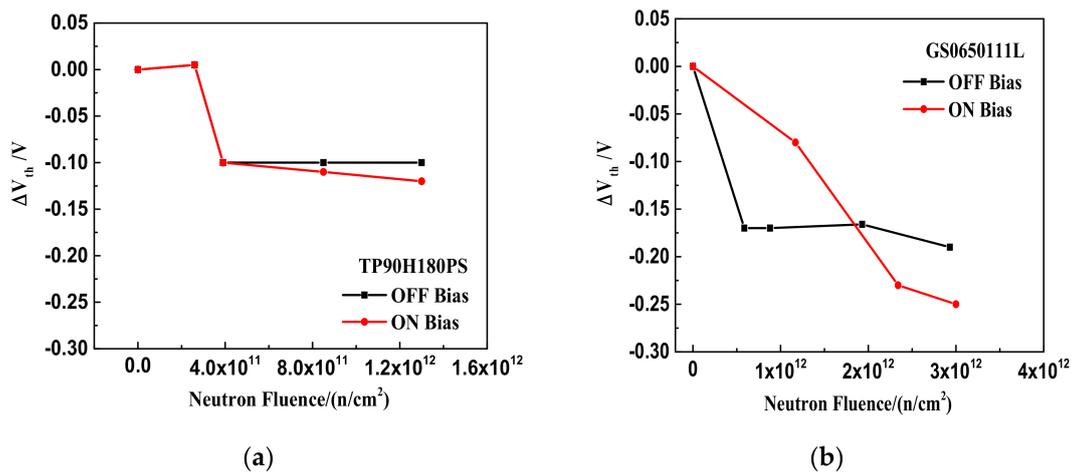


Figure 4. The relationship between the threshold voltage shifts of the device and the neutron irradiation under the on-state and off-state: (a) TP90H180PS and (b) GS0650111L.

3.2. ⁶⁰Co Gamma-Ray Irradiation

After neutron irradiation, the TID effect of the GaN HEMT based on the p-GaN gate and the cascode structure were studied under the same bias condition using gamma-ray irradiation for a week. The electrical characteristics of the devices were tested before gamma irradiation. The pre-irradiation leakage currents were about 1.9 μ A for TP90H180PS and 300 nA for GS0650111L under the off state, respectively, which were mostly consistent with those after neutron irradiation. It indicated that no annealing effect occurred in a week. Two types of devices without neutron irradiation were gamma-ray irradiated to study the influence of neutron irradiation on the TID effect. The fluences of neutron radiation are 1.3×10^{12} n/cm² for TP90H180PS and 3×10^{12} n/cm² for GS0650111L, respectively. The leakage current variations as the function of the accumulated TID dose and the DDD fluence are shown in Figure 5. The devices are biased on off-state ($V_{ds} = V_{gs} = 0$ V) and on-state ($V_{ds} = 1$ V, $V_{gs} = 2.6$ V) during irradiation, respectively. Figure 5a shows that when accumulated gamma-ray doses are up to 800k rad(Si), the leakage current of TP90H180PS biased on on-state is little changed under the combined effect of neutron and gamma-ray irradiation. However, the leakage current variation of TP90H180PS at off-state bias is 10 nA under the combined effect of the neutron and gamma-ray, which is less than 8 μ A under the gamma-ray radiation and 280 nA under the neutron radiation. After 168 h of annealing at room temperature, the leakage current of the device mostly recovers to the normal value. As is shown in Figure 5b, exposed to accumulated gamma-ray doses to 800k rad(Si), the leakage current of GS0650111L at off-state bias is also much the same under the combined effect of neutron and gamma-ray irradiation. In constant, the leakage current of GS0650111L at on-state bias increases by 75 μ A under the gamma-ray radiation at accumulated doses of 1M rad(Si). After annealing for 50 h at the on-state bias under gamma-ray irradiation, the leakage current mostly recovered to the normal value. However, at off-state bias the leakage current increases by 15 μ A under the gamma-ray irradiation, 90 nA under the neutron radiation, and 100 μ A under the combined effect of neutron and gamma-ray irradiation. While the device's performance test passes after the TID annealing.

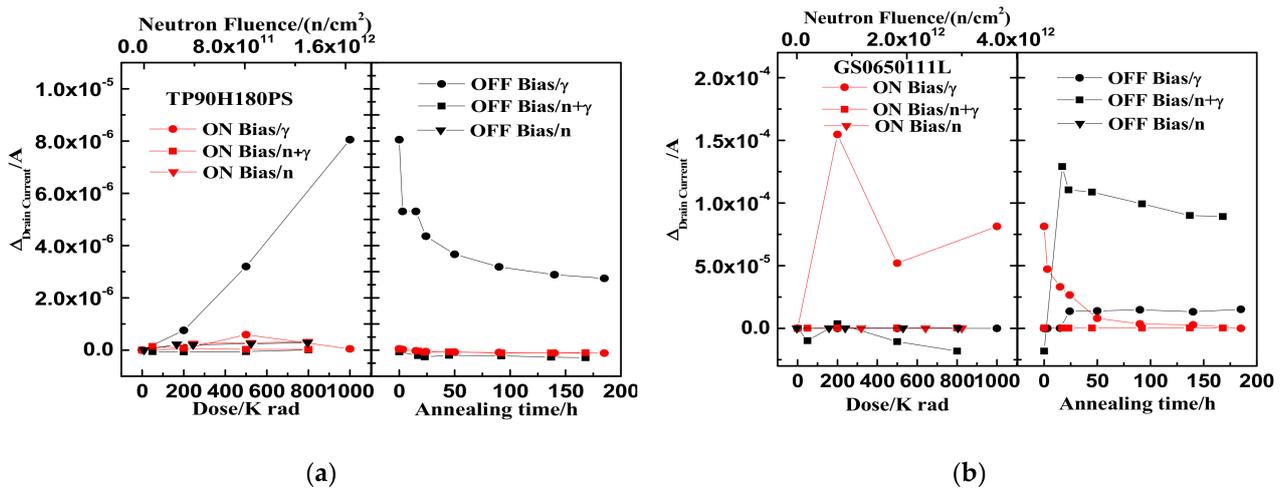


Figure 5. The variations of drain current with the neutron and gamma-ray irradiation and 168 h annealing under the on-state and off-state: (a) TP90H180PS and (b) GS0650111L.

Figure 6 shows the threshold voltage shifts of TP90H180PS and GS0650111L as the function of accumulated TID dose and the neutron irradiation fluence. As shown in Figure 6a, when gamma-ray doses accumulate to 800k rad(Si), the threshold voltage of TP90H180PS at on-state bias negatively shifted about 6 V under the combined effect of neutron and gamma-ray irradiation, about 4.5 V under the gamma-ray irradiation and about 0.1 V under the neutron irradiation. While the threshold voltage of TP90H180PS at off-state bias both shifted about -1.7 V, under the combined effect of neutron and gamma-ray irradiation and the gamma-ray irradiation. After annealing at room temperature for 168 h, the threshold voltage of the device is still negatively shifted under the on and off state. The device's function is abnormal after TID annealing. As shown in Figure 6b, when gamma-ray doses accumulate to 800k rad(Si), the threshold voltage of GS0650111L is little changed. In addition, under the combined effect of neutron and gamma-ray irradiation, the threshold voltage of GS0650111L biased on on-state shows a negative shift of about 0.3 V. After annealing at room temperature for 168 h, the threshold voltage returned to normal value and the device's functional test passed.

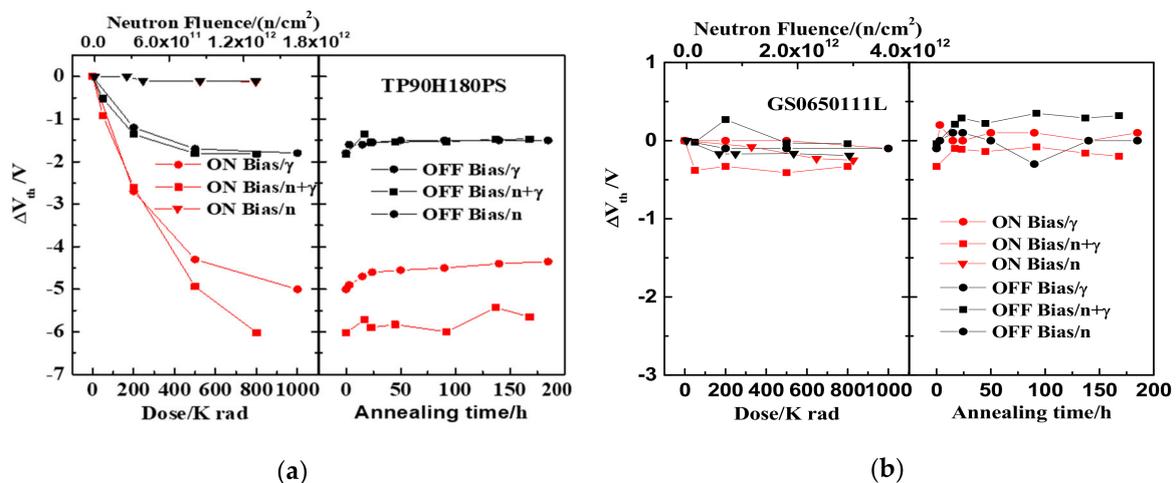


Figure 6. The variations of threshold voltage with the neutron and gamma-ray irradiation and 168 h annealing under the on-state and off-state: (a) TP90H180PS and (b) GS0650111L.

4. Discussion

Figures 3 and 4 show that the leakage current and the threshold voltage of the two-type GaN HEMTs exhibit slight degradation under neutron irradiation. It indicates that the

two-type GaN HEMTs are not very sensitive to the DDD effect when the accumulated fluence is up to 1.3×10^{12} n/cm². Additionally, the leakage current variations and the threshold voltage offsets of the two types of devices have little difference between on-state and off-state cases during the neutron irradiation. Some previous studies showed that the vacancy defect and interstitial atom defect produced by the DDD effect would cause the leakage current and threshold voltage degradation in silicon devices. Moreover, the initial defect concentrations produced by the DDD effect are independent of the bias applied [12,13]. This may be the possible reason why the bias voltage of the two-type GaN HEMTs is not very sensitive to the DDD effect.

An analysis of data in Figure 5 shows that the drain current degradation of the GaN HEMT based on the cascode structure and the p-GaN gate exposed to both DDD and TID effect at accumulated gamma-ray doses of 800k rad(Si) exhibit obviously lower than the sum of the two separated effects. It indicates that the cascode structure and the p-GaN gate GaN HEMT are sensitive to the synergistic effect of DDD and TID. Further analysis of the internal circuit structure of GaN HEMT based on the cascode structure can be seen in Figure 7a. The circuit is composed of a low-voltage silicon metal–oxide–semiconductor field-effect transistor (MOSFET) and high voltage depletion-mode GaN HEMT. Figure 7b shows a cross-sectional view of the low-voltage silicon MOSFET extracted by the scanning electron microscope (SEM). It can be found that the low-voltage silicon MOSFET is an N-channel MOSFET with a trench structure. Under the off state, the drain-gate terminal of the depletion-mode GaN HEMT and the source-drain channel of silicon MOSFET is the main current-leakage paths. Previous reports [14–16] showed that N-channel MOSFET is very sensitive to TID and that the drain current increases with the accumulated gamma-ray dose. In addition, the defect caused by neutron irradiation in the silicon layer and Si-SiO₂ interface could lead to an increase in the channel resistance and a decrease in the carriers' mobility in the MOSFET device. Consequently, the leakage current of GaN decreases. This is a possible reason why the drain current of the GaN HEMT based on the cascode structure is obviously suppressed under the synergistic effect of the DDD and TID effect.

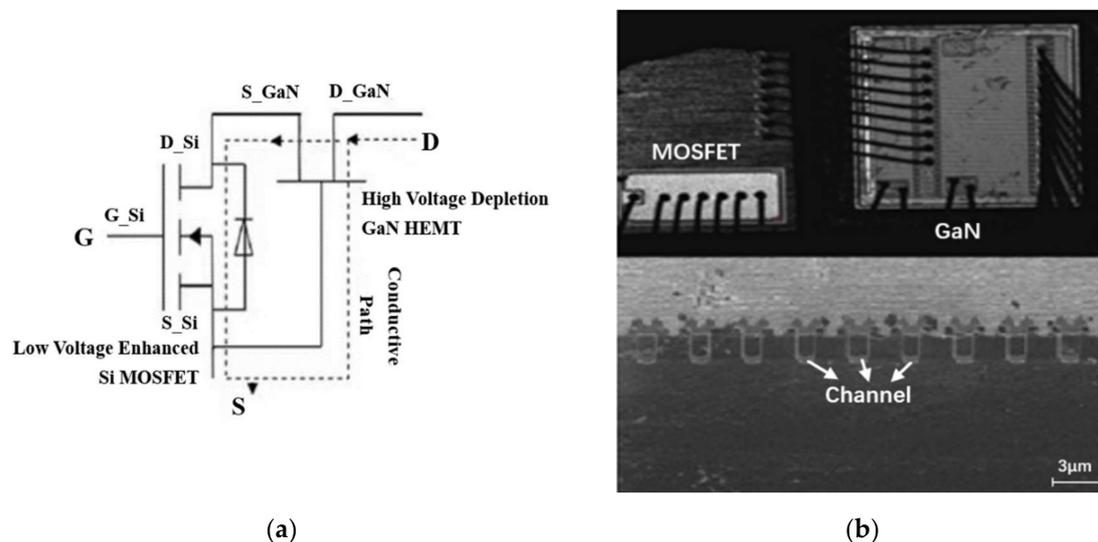


Figure 7. Schematic diagram of (a) the circuit structure of the GaN HEMT based on the cascode structure and (b) the internal MOSFET cross-section.

The distribution of radiation-induced charges and defects in p-GaN gated GaN HEMT under the synergistic effect of DDD and TID effect is shown in Figure 8. During gamma-ray irradiation, electron-hole pairs are generated in the passivation layer of the device. Under the forward gate electric field, the generated holes drift towards the interface of the passivation layer and the AlGaN barrier layer. These holes could be captured by deep-level traps near the interface, forming the trapped charges. Additionally, this could lead to the

form of the built-in electric field between the passivation layer and the channel region. The direction of the built-in electric field is opposite to that of the external gate electric field, which would reduce the depletion effect of the p-GaN layer on two-dimensional electron gas (2DEG). Thus, the leakage current in the source-drain channel increases. Meanwhile, during the neutron irradiation, bulk defects and interface defects are possibly produced in the AlGaN barrier layer, the GaN buffer layer, the passivation layer, and the AlGaN/GaN interface. This will result in an increase in the channel resistance and the degradation of the 2DEG mobility, further leading to a leakage current decrease. This may be the main reason why the drain current of the p-GaN type GaN HEMT decreases significantly under the synergistic effect of the DDD and TID effect.

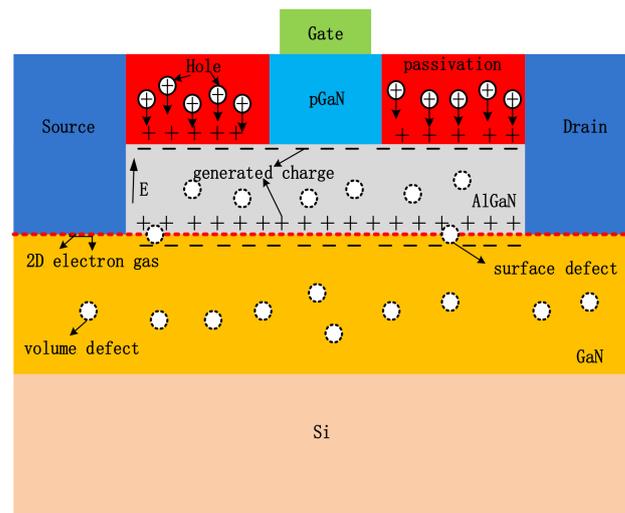


Figure 8. Schematic diagram of the electron-hole pairs transport process induced by the interaction of neutrons and gamma-rays in GaN HEMT.

Analyzing the data in Figure 6, it is interesting that the negative shift of the threshold voltage of the GaN HEMT based on the cascode structure is -6.0 V under the combined effect of neutron and gamma-ray. This value is not equal to -4.6 V, which is the sum of the threshold voltage shift caused by the neutron and the gamma-ray irradiation. It confirms that GaN HEMT has an obvious synergistic effect on DDD and TID effects. Previous studies [17–22] have shown that neutron irradiation and gamma-ray irradiation could lead to a negative shift of the threshold voltage in the N-channel MOSFET and a positive voltage shift in the depletion mode GaN HEMT. Additionally, MOSFET is more sensitive to neutron and gamma-ray irradiation than the depletion mode GaN HEMT, leading to the negative shift of the threshold voltage of GaN HEMT based on the cascode structure under the synergistic effect of DDD and TID effect. Figure 9 shows the distribution of the radiation-generated charge in the N-channel MOSFET induced by the synergistic effect of the DDD and TID effects. Electron-hole pairs are generated in the oxide layer of the MOSFET under gamma-ray irradiation. Electrons rapidly move to the gate electrode and the holes quickly move to the SiO_2/Si interface under the positive electric field at the gate port. During this processing, electrons are captured by the donor traps in the oxide layer, forming the oxide trap charges, and holes are captured by the acceptor traps in the SiO_2/Si interface, forming the interface trap charges. The shift of the threshold voltage resulting from charge trapping in the MOSFET can be calculated according to (1).

$$\Delta V_{th} = \frac{d_{ox} g q}{\epsilon_{SiO_2}} (\Delta N_{ot} - \Delta N_{it}) \quad (1)$$

where ϵ_{SiO_2} is the dielectric constant of SiO_2 , q is the elementary charge, d_{ox} is the oxide layer thickness, ΔN_{ot} is the number of the radiation-induced oxide trap charge and ΔN_{it} is the number of the radiation-induced interface charge. The negative V_{th} shift is proportional

to the net charge accumulation caused by radiation in the oxide layer, which is the main reason for the negative V_{th} shift in the MOSFET. When exposed to neutron irradiation, different types of defects are produced in the oxide layer, increasing the defect density in the device [23,24]. These radiation-induced defects may capture the holes induced by gamma-ray irradiation and further increase the number of trap charges in the oxide layer. This may be responsible for the obvious increase in the threshold voltage negative shift under the synergistic effect of the DDD and TID effects. While the V_{th} shift of the p-GaN type GaN HEMT is about -0.2 V under the synergistic effect of DDD and TID effects. The value is mostly the same as the sum of the threshold voltage shift caused by the single neutron and gamma-ray irradiation. When the GaN HEMT is exposed to neutron irradiation, donor traps are produced [25,26] in the p-GaN layer, which weakens the depletion effect of p-GaN on 2DEG, leading to a negative shift of the threshold voltage. For the gamma-ray irradiation, additional insulating layers and interface traps are produced in the insulating layer and the insulating layer/AlGaIn interface. Because of the thin gate insulator layer and the low transfer rate of the interface trap charge, the number of the radiation-generated charges is greatly suppressed, which is hard to impact on the 2DEG in the channel, leading to the change of the threshold voltage [27,28]. Therefore, the negative V_{th} shift of p-GaN GaN HEMT caused by the synergistic effect of DDD and TID effect is mainly affected by neutron irradiation.

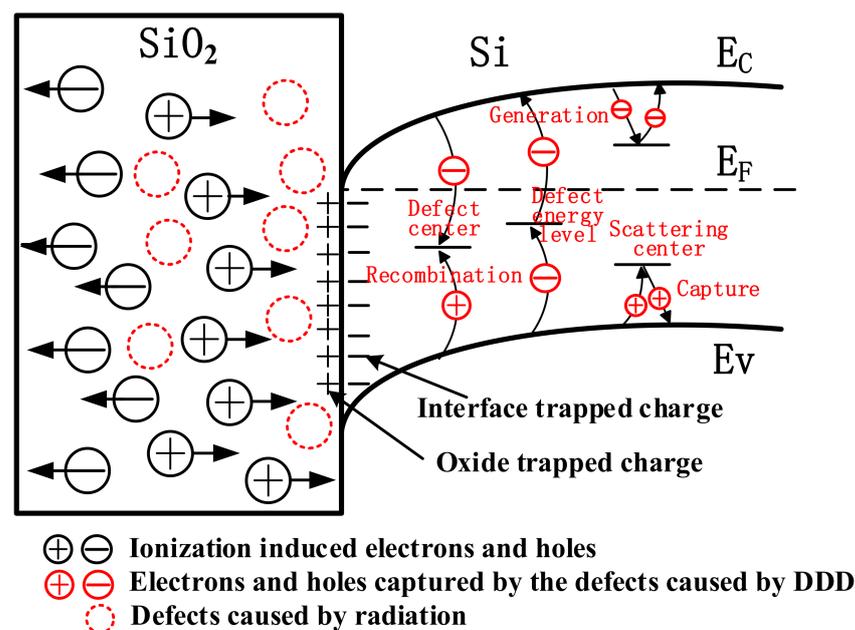


Figure 9. Distribution of charge in N-channel MOSFET induced by the synergistic effect of gamma-ray and neutron.

5. Conclusions

This work investigated the synergistic effect of the DDD and TID effects for enhancement-mode GaN HEMT based on the p-GaN gate and the cascode structure using a 14 MeV neutron high voltage multiplier and ^{60}Co gamma-ray irradiation. The influence of the DDD effect on the TID effect of GaN HEMT with different structures under the on-state and off-state were investigated. The experimental results show that the GaN HEMT based on the cascode structure is much more susceptible to the synergistic effect of the DDD and TID effects than the p-GaN gate GaN HEMT. Additionally, the failure mechanisms of the synergistic effect of the DDD and TID effects were proposed. The bulk and interface defects caused by neutron irradiation in the GaN HEMT will lead to an increase in channel resistance and the degradation of 2DEG mobility, which inhibits an increase in the drain current. This may be the main reason why the drain current of the GaN HEMT based on

the p-GaN gate structure decreases significantly under the synergistic effect of the DDD and TID effects. In addition, Si MOSFET is a possible reason why the cascode structure GaN HEMT is sensitive to the synergistic effect of the DDD and TID effects. Defects in the oxide layer induced by neutron irradiation may capture the holes induced by gamma-ray irradiation, leading to a further increase in the number of oxide trap charges. This may be the reason for the significant increase in the threshold voltage shift of the cascode structure GaN HEMT.

Author Contributions: Data curation, Q.L. and Q.C.; formal analysis, X.W. and R.Y.; project administration, J.H.; validation, H.W.; visualization, Z.W.; writing—original draft, R.C.; writing—review and editing, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Foundation of Key Laboratory of the Chinese Academy of Sciences (E12130101S), the National Natural Science Foundation of China (11875060), and the Beijing Municipal Commission of Science and Technology (Grant No. E039360101).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available in a publicly accessible repository.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ishida, T. GaN HEMT Technologies for Space and Radio Applications. *Microw. J.* **2011**, *54*, 54–66.
2. Ajayan, J.; Nirmal, D.; Ramesh, R.; Bhattacharya, S.; Tayal, S.; Leo Joseph, L.M.I.; Thoutam, L.R.; Ajitha, D. A critical review of AlGaIn/GaN-heterostructure based Schottky diode/HEMT hydrogen (H₂) sensors for aerospace and industrial applications. *Measurement* **2021**, *186*, 110100. [[CrossRef](#)]
3. Maset, E.; Ejea, J.B.; Ferreres, A.; Lizán, J.L.; Blanes, J.M.; Sanchis-Kilders, E.; Garrigós, A. Optimized Design of 1 MHz Intermediate Bus Converter Using GaN HEMT for Aerospace Applications. *Energies* **2020**, *13*, 6583. [[CrossRef](#)]
4. Sun, R.; Liang, Y.C. Design of power integrated circuits in full AlGaIn/GaN MIS-HEMT configuration for power conversion. *Phys. Status Solidi A* **2016**, *214*, 1600562. [[CrossRef](#)]
5. Ding, L.; Gerardin, S.; Bagatin, M.; Bisello, D.; Mattiazzo, S.; Paccagnella, A. Investigation of total ionizing dose effect and displacement damage in 65nm CMOS transistors exposed to 3MeV protons. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* **2015**, *796*, 104–107. [[CrossRef](#)]
6. Virmondois, C.; Goiffon, V.; Magnan, P.; Saint-Pe, O.; Girard, S.; Petit, S.; Rolland, G.; Bardoux, A. Total Ionizing Dose Versus Displacement Damage Dose Induced Dark Current Random Telegraph Signals in CMOS Image Sensors. *IEEE Trans. Nucl. Sci.* **2011**, *58*, 3085–3094. [[CrossRef](#)]
7. Taggart, J.L.; Jacobs-Gedrim, R.B.; McLain, M.L.; Barnaby, H.J.; Bielejec, E.S.; Hardy, W.; Marinella, M.J.; Kozicki, M.N.; Holbert, K. Failure Thresholds in CBRAM Due to Total Ionizing Dose and Displacement Damage Effects. *IEEE Trans. Nucl. Sci.* **2019**, *66*, 69–76. [[CrossRef](#)]
8. Topper, A.D.; Campola, M.J.; Chen, D.; Casey, M.C.; Yau, K.-Y.; Cochran, D.J.; LaBel, K.A.; Ladbury, R.L.; Mondy, T.K.; O'Bryan, M.V.; et al. Compendium of Current Total Ionizing Dose and Displacement Damage Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program. In Proceedings of the IEEE Radiation Effects Data Workshop (REDW), New Orleans, LA, USA, 17–21 July 2017; pp. 1–11. [[CrossRef](#)]
9. Butler, P.A.; Uren, M.J.; Lambert, B.; Kuball, M. Neutron Irradiation Impact on AlGaIn/GaN HEMT Switching Transients. *IEEE Trans. Nucl. Sci.* **2018**, *65*, 2862–2869. [[CrossRef](#)]
10. Kruse, W.G. Radiation dosimeters developed for snap ioa flight test. *IEEE Trans. Nucl. Sci.* **1966**, *NS13*, 230. (in English). [[CrossRef](#)]
11. Long, L.; Zheng, S.; Jing, S.; Shouzhi, Z. Research on Dose Space Distribution of Russian Nuclear-Powered Cruise Missile. *Nucl. Sci. Eng.* **2020**, *40*, 9.
12. Hopkinson, G.R. Cobalt60 and proton radiation effects on large format, 2-d, ccd arrays for an earth imaging application. *IEEE Trans. Nucl. Sci.* **1992**, *39*, 2018–2025. (in English). [[CrossRef](#)]
13. Barde, S.; Ecoffet, R.; Costeraste, J.; Meygret, A.; Hugon, X. Displacement damage effects in InGaAs detectors: Experimental results and semi-empirical model prediction. *IEEE Trans. Nucl. Sci.* **2000**, *47*, 2466–2472. [[CrossRef](#)]
14. Mo, J.; Chen, H.; Wang, L.; Yu, F. Total Ionizing Dose Effect and Single Event Burnout of VDMOS with Different Inter Layer Dielectric and Passivation. *J. Electron. Test.—Theory Appl.* **2017**, *33*, 255–259. [[CrossRef](#)]
15. Li, X.; Jia, Y.; Zhou, X.; Tang, Y.; Li, Y.; Liu, G.; Jia, G. Degradation of Radiation-Hardened Vertical Double-Diffused Metal-Oxide-Semiconductor Field-Effect Transistor During Gamma Ray Irradiation Performed After Heavy Ion Striking. *IEEE Electron Device Lett.* **2019**, *41*, 216–219. [[CrossRef](#)]

16. Mo, J.; Zhao, X.; Min, Z. Total Ionizing Dose Effects of Si Vertical Diffused MOSFET with SiO₂ and Si₃N₄/SiO₂ Gate Dielectrics. *Act. Passiv. Electron. Compon.* **2017**, *2017*, 9685685. [[CrossRef](#)]
17. Blackburn, D.L.; Robbins, T.C.; Galloway, K.F. VDMOS Power Transistor Drain-Source Resistance Radiation Dependence. *IEEE Trans. Nucl. Sci.* **1981**, *28*, 4354–4359. [[CrossRef](#)]
18. Sakai, T.; Yachi, T. Effects of gamma-ray irradiation on thin-gate-oxide VDMOSFET characteristics. *IEEE Trans. Electron Devices* **1991**, *38*, 1510–1515. [[CrossRef](#)]
19. Lu, L.; Zhang, J.C.; Xue, J.S. Neutron irradiation effects on AlGaIn//GaIn high electron mobility transistors. *Chin. Phys. B* **2012**, *21*, 360–364. [[CrossRef](#)]
20. Lv, L.; Yan, X.; Cao, Y.; Zhu, Q.; Yang, L.; Zhou, X.; Ma, X.; Hao, Y. Significant Degradation of AlGaIn/GaIn High-Electron Mobility Transistors With Fast and Thermal Neutron Irradiation. *IEEE Trans. Nucl. Sci.* **2019**, *66*, 886–891. [[CrossRef](#)]
21. Yan-Ping, W.; Yin-Hong, L.; Wei, W.; Ke-Ying, Z.; Hong-Yia, G.; Xiao-Qiang, G.; Yuan-Ming, W. ⁶⁰Co gamma radiation effect on AlGaIn/AlN/GaIn HEMT devices. *Chin. Phys. C* **2013**, *37*, 056201.
22. Min, K. Effects of Gamma-Ray Irradiation on Electronic Characteristics of AlGaIn/GaIn Heterostructures. In Proceedings of the International Workshop on Nitride Semiconductors (IWN-2016), Orlando, FL, USA, 2–7 October 2016.
23. Witteles, A.A. Neutron Radiation Effects on MOS Fets: Theory and Experiment. *IEEE Trans. Nucl. Sci.* **1968**, *15*, 126–132. [[CrossRef](#)]
24. Ahaitouf, A.; Losson, E.; Charles, J.-P. DLTS and capacitance transients study of defects induced by neutron irradiation in MOS structures CCD process. In Proceedings of the 1999 Fifth European Conference on Radiation and Its Effects on Components and Systems. RADECS 99 (Cat. No.99TH8471), Fontevraud, France, 13–17 September 1999. [[CrossRef](#)]
25. Polyakov, A.Y.; Smirnov, N.B.; Govorkov, A.V.; Markov, A.V. Neutron irradiation effects in p-GaIn. *J. Vac. Sci. Technol. B* **2006**, *24*, 2256–2261. [[CrossRef](#)]
26. Kuriyama, K.; Tokumasu, T.; Sano, H.; Okada, M. Ion channeling and Raman scattering studies of the lattice disorder and residual strain in neutron irradiated GaIn. *Solid State Commun.* **2004**, *131*, 31–35. [[CrossRef](#)]
27. Shi, Y.; Chen, W.; Sun, R.; Liu, C.; Xin, Y.; Xia, Y.; Wang, F.; Xu, X.; Deng, X.; Chen, T.; et al. Modeling the Influence of the Acceptor-Type Trap on the 2DEG Density for GaIn MIS-HEMTs. *IEEE Trans. Electron Devices* **2020**, *67*, 2290–2296. [[CrossRef](#)]
28. Hachatrian, A.K.; Koehler, A.D.; Anderson, T.J. Displacement Damage and Single Event Effects in AlGaIn/GaIn HEMTs, State-Of-The-Art Program On Compound Semiconductors 59 (SOTAPOCS 59). *ECS Trans.* **2017**, *75*, 13–20.