Simulation Study on the Mechanisms of Proton-Induced Single Event Effects in GaN HEMT

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Date: 2026-01-22T10:24:39+00:00

Abstract

This paper constructs a multi-layer structural model of GaN HEMT based on Geant4 to simulate the distributions of mass number A, charge number Z, kinetic energy E_k, and linear energy transfer (LET) of secondary particles reaching the GaN sensitive layer after 10$ 500*MeVprotonsincidentinthegate, source − gategap, anddrainregions.Theresultsindicatethatwhen*10 200*MeVprotonsareincidentonthedrainatanglesof*
gategap, anddrainregionswithprotonsofdifferentenergiesrevealthatthegateismostsensitivetoenergyvariati
LET(>$ 15 MeV~cm^2/mg) events increasing from 5% to 15%, representing a 200% increase in the 10$ $50 MeV range, attributed to the enhanced nuclear reaction yield by high-Z overlayers; the source-gate gap shows intermediate sensitivity with a change rate of 18%; and the drain is the least sensitive, only obvious increase in high-LET interval. These quantitative patterns reveal the microscopic influences of overlayer materials and geometric structures on secondary particle transport, providing a physical basis for explaining threshold issues such as SEGR and SEB.

Full Text

Preamble

Simulation Study on the Mechanisms of Proton-Induced Single Event Effects in GaN HEMT∗ Li Li,1, † Zheng Zhang,1 and Gang Guo1 1Department of Nuclear Physics, China Institute of Atomic Energy, Beijing 102413, China This paper constructs a multi-layer structural model of GaN HEMT based on Geant4 to simulate the distri- butions of mass number A, charge number Z, kinetic energy Ek, and linear energy transfer (LET) of secondary particles reaching the GaN sensitive layer after 10 500 MeV protons incident in the gate, source-gate gap, and drain regions. The results indicate that when 10 200 MeV protons are incident on the drain at angles of 0 ◦ 60 ◦ , the angular effect is smoothed out in the sensitive layer, with deviations in the average A and Z less than 10% between angles. This is primarily due to the cumulative attenuation from multiple

Coulomb scattering and energy loss in the overlying layers. Furthermore, vertical irradiations on the gate, source-gate gap, and drain regions with protons of different energies reveal that the gate is most sensitive to energy variations, with the pro- portion of high-LET(> 15 MeV cm2/mg) events increasing from 5% to 15%, representing a 200% increase in the 10 50 MeV range, attributed to the enhanced nuclear reaction yield by high-Z overlayers; the source-gate gap shows intermediate sensitivity with a change rate of 18%; and the drain is the least sensitive, only obvious increase in high-LET interval. These quantitative patterns reveal the microscopic influences of overlayer materi- als and geometric structures on secondary particle transport, providing a physical basis for explaining threshold issues such as SEGR and SEB.

Keywords: GaN HEMT, proton radiation, single event effect, high-Z fragment, Geant4 simulation

INTRODUCTION

GaN high electron mobility transistors (HEMTs) out- perform traditional Si devices in high-frequency and high- temperature applications due to their wide band gap, high critical breakdown field, and the high conductivity and ex- cellent thermal stability of the two-dimensional electron gas [1, 2]. Compared to GaAs, GaN has higher thermal conduc- tivity, and makes the overall performance of the device more promising in high-voltage environments [1]. Hence, GaN HEMTs have attracted significant attention for applications in radiation environments such as space electronics, power conversion , and RF front-ends of nuclear power plant[3].

Existing research on non-single-event radiation effects (such as total ionizing dose and displacement damage) has provided representative conclusions at the material and de- vice levels. For example, Ionascut-Nedelcescu et al. sys- tematically evaluated the radiation tolerance of GaN through material and device samples, highlighting its intrinsic hard- ness advantages under various irradiation and establishing a baseline for device-level assessments [1]. Regarding degra- dation mechanisms and energy window selection, Liu et al. conducted proton irradiation experiments on AlGaN/GaN HEMTs with different energies, revealing the sensitivity pat- terns of DC and RF parameters to proton energy regions under fixed flux, thereby guiding test energy selection and degradation interpretation [3]. In terms of bias and total dose cou- pling, Jiang et al. compared the worst-case bias conditions under proton and 10-keV X-ray irradiations, noting that sub- strate and structural differences can lead to different degrada- tion paths and threshold positions, emphasizing the need to ∗ Supported by CNNC' s R&D platform steadily supports scientific re- search projects(WDZC-2024-056, WDZC-2023-AW-0201); National Nat- ural Science Foundation of China(No. 12405323), and the Fund of Inno- vation Center for Radiation Application(KFZC2023021201). † E-mail: lili@ciae.ac.cn. combine bias with irradiation to determine degradation limits Research on the sensitivity of GaN HEMTs to single event effects (SEEs) mainly focuses on mechanisms induced by heavy ions and protons. Kuboyama et al. observed single- event damage in AlGaN/GaN HEMTs through heavy-ion ir- radiation experiments, pointing out that regions near the gate and drain are more prone to irreversible failures, emphasizing the decisive role of local device structures in event thresholds [5]. For commercial power devices, Mizuta et al. con- ducted heavy-ion tests on multiple GaN HEMTs, evaluating the behavior of SEE and potential failure sites below the rated voltages, and noting that the mechanisms of “normally-off” structures require further experimental and theoretical sup- port [6]. Recent reviews and device-level studies indicate that GaN HEMTs are susceptible to issues such as heavy- ion-induced single-event burnout (SEB), single-event gate rupture (SEGR), transient currents, and parasitic channels, which need to be addressed through quantitative energy de- position parameters combined with material structures and event statistics [7]. Additionally, Osheroff et al. systemati- cally characterized the LET and range of proton-induced re- coil ions in GaN, showing that compared to Si, GaN exhibits higher LET limits and larger high-LET interval statistics about 20% higher than Si in higher energy regions, providing numerical references for SEE mechanism studies in proton environments [8]. Proton irradiation studies on GaN-based MIS-HEMTs further emphasize reliability impacts from LET variations [9]. High-Z materials in the upper layers of devices can produce short-range, high-LET ions under proton induc- tion, forming secondary SEE risks. Ladbury et al. proposed an evaluation method based on mission proton spectra and high-Z nuclear reaction cross-sections, combined with metal layer thickness, overlayer dielectrics, and sensitive volume geometry, to calculate equivalent LET distributions, defining destructive and non-destructive SEE risks, and highlighting the weakening effect of overlayers on high-Z fragments [10].

Distinguishing internal recoils from exogenous high-Z frag- ments is crucial for system-level radiation-hardened design of GaN devices.

Recent experiments have further revealed the specific im- pacts of proton radiation on GaN HEMT SEEs, for example, Zhang et al. observed a significant reduction in SEB thresh- olds after proton irradiation (decreasing 15 20% from ini- tial values), attributed to positive charge accumulation and defect-induced parasitic channels [11]. Wang et al. discussed the coupling effects of pre-stress, LET, and gate voltage on SEEs, noting that negative gate voltage can amplify gate sen- sitivity [12]. Huang et al. analyzed the SEB mechanisms of p-GaN gate HEMTs through experiments and TCAD simula- tions, emphasizing the amplifying role of buffer layer defects in high-LET events [13]. Wu et al. compared damages from protons and heavy fragments on Cascode GaN HEMTs, quan- tifying defect density increases from 3.27\$×1016$cm-3eV-1to7.17$×\$1016 cm−3 eV−1, and discussing threshold degrada- tion under synergistic irradiation [14]. Huang et al. studied degradation mechanisms under synergistic proton and heavy- ion irradiation, revealing the dominant role of proton contri- butions in secondary particle generation [15].

Although existing literature has accumulated clear expe- riences in total dose and displacement damage, research on SEEs in GaN HEMTs lacks a unified microscopic mechanism framework, especially regarding secondary particle transport, energy deposition distributions under proton irradiation, and their spatial differences in gate, source-gate gap, and drain regions. These quantitative data are foundational for inter- preting event thresholds and cross-sections, and influence energy-angle testing windows, local structural optimization, and packaging selection. In this study, Geant4 was employed to simulations a multi-layer model of GaN HEMTs, setting analysis windows in the gate, gap region, and drain to obtain the distribution functions of A, Z, Ek, and LET incident on the GaN sensitive layer; analyzes multi-angle incidences of 10 200 MeV protons, revealing angular effects in the sen- sitive layer under different proton energies, as well as sensi- tivity differences caused by irradiations in different regions.

These results provide a physical basis for GaN HEMT SEE mechanism analysis and radiation-hardened design. Com- pared to existing work, this paper quantifies the characteris- tics of angular effect attenuation and its energy dependence through regionalized analysis, bridging microscopic particle distributions with device-level SEE threshold degradations.

II. THEORETICAL BACKGROUND A. Microscopic Mechanisms of Proton on GaN HEMT When protons are incident on the multi-layer structure of GaN HEMTs, energy deposition is primarily dominated by electromagnetic interactions and nuclear reactions. The av- erage ionization energy loss can be described by the Bethe- Bloch formula[16]: 4πz2e4ρZ mev2A (cid:20) (cid:18) 2mev2 (cid:19) I (1 − $ $2) − $ $2 − (cid:21) where Z is the proton charge number, β = v/c is the rela- tivistic factor, I is the average excitation energy of the target material, and δ is the density effect correction. Energy loss in thin layers follows the Landau-Vavilov distribution[17], exhibiting long-tail characteristics, especially amplifying lo- cal energy fluctuations in shallow layers, thereby increasing the probability of threshold events. Angular broadening is dominated by multiple Coulomb scattering, with the root- mean-square scattering angle $ $0 approximated by the High- land formula[18]: $ $0 (cid:39) 13.6MeV (cid:114) x (cid:20) 1 + 0.038 ln (cid:19)(cid:21) (cid:18) x where p is the momentum, and X0 is the radiation length. Cumulative small-angle scattering dominates direc- tional broadening, making angular effects most significant in shallow layers, with gradual attenuation as layer depth in- creases.

Elastic and inelastic reactions of protons with Ga and N nu- clei produce secondary recoil ions, altering particle composi- tion and LET distributions. Compared to Si, the high atomic number of Ga in GaN (Z=31) leads to higher LET limits and shorter ranges for recoil ions, which is the fundamental reason for differences in SEE thresholds between GaN and Si experiences. This study focuses on four observables: average mass number ¯A and charge number ¯Z (representing ion com- position), average kinetic energy ¯Ek (determining penetration and track length), and average LET (linking microscopic de- position to SEE thresholds), defined as: (cid:88) (cid:88) (cid:88) Ek,i, L ¯ET =

(cid:88) Among them, N is the total number of particles reaching the analysis window, and is the step-length energy loss of the i-th particle. These quantities bridge microscopic processes with device effects, providing a quantitative basis for subse- quent energy deposition distribution analysis and used in re- sults to evaluate SEE event probabilities.

B. Model and Simulation Calculations Based on a typical GaN HEMT structure, as shown in Fig- ure 1, the model includes an overlayer (280nm Au in gate, and 20 nm Au in drain, density 19.3 g/cm3; 50 nm Ni, density 8.9 g/cm3), AlGaN barrier layer (25 nm, density 5.5 g/cm3), and 1500 nm GaN layer (density 6.15 g/cm3), which is the sensi- tive volume, with lateral dimensions matching the beam spot (10 µm × 10 µm). Analysis regions are located at: 1(cid:13) gate region (restricted by Au/Ni overlayer and AlGaN barrier); 2(cid:13) source-gate gap region(The stacking sequence is the same as Fig. 1 [Figure 1: see original paper]. Schematic of GaN HEMT Device Structure and Incident Sites. drain-gate region); 3(cid:13) drain region. Simulated incident par- ticles are parallel monoenergetic proton beams, with energy range 10 500 MeV, angles of 0°, 30°, 45°, and 60°, simulat- ing 109 events per condition.

Fig. 2 [Figure 2: see original paper]. Distributions of A, Z, Ek, and LET (Normalized Counts dN/dX) of Secondary Particles Entering the GaN Sensitive Layer for 10 MeV Protons Incident on the Drain at Different Angles (0°, 30°, 45°, 60°). simulation This work [19]. uses Geant4 Electromagnetic processes calcula- employ the tions G4EmStandardPhysics_option4 package, including en- ergy loss fluctuations, shell effects, and low-energy electron production, supporting accurate multiple scattering calcula- tions in micron-scale geometries; nuclear reaction processes use the QGSP_{{{BIC}}_{{HP}}} list, suitable for MeV-level nucleon- nucleon interaction reactions, including intranuclear cascade collisions and compound nucleus evaporation [20]. The simulation detector uses G4VSensitiveDetector to record A, Z, Ek, and LET for each event at the GaN layer boundary trajectory-restricted energy loss dE/dx, (calculated as tracking secondary particles with Ek > 1 keV, optimizing computation with electron low-energy cutoff). Data output uses G4AnalysisManager for statistics, with fixed random seeds to ensure reproducibility. Model validation: LET distri- butions are consistent with Osheroff et al. [8] . These settings ensure the reliability of simulation results, reflecting energy deposition in real device sensitive volumes, complementing experimental SEE thresholds .

III. RESULTS AND DISCUSSION Influence of Incident Angle and Energy on Deposition First, we simulated protons of 10 MeV, 100 MeV, and 200 MeV energies incident on the device drain at different angles, obtaining the distribution functions of mass number A, charge number Z, kinetic energy Ek, and linear energy transfer LET of secondary particles entering the GaN sensitive layer.

Fig.2 to Fig.4 show the distributions of A, Z, Ek, and LET under 10 MeV, 100 MeV, and 200 MeV proton ener- gies at different angles, respectively. Because of As shown in the figures, when the incident angle increases, the distribution functions entering the GaN sensitive layer are consistent in most intervals except for obvious differences in a few, indi- cating that after protons incident through the drain top, under- going multiple scattering and energy transfer dissipation, the angular effects on mass number, charge number, energy, and LET values in the sensitive layer are all “smoothed out” .The merging of curves around the LET =1.9 2.1 MeV cm2/mg Fig. 3 [Figure 3: see original paper]. Distributions of A, Z, Ek, and LET (Normalized Counts dN/dX) of Secondary Particles Entering the GaN Sensitive Layer for 100 MeV Protons Incident on the Drain at Different Angles (0 ∘ , 30 ∘ , 45 ∘ , 60 ∘). corresponds to the minimum ionizing particle (MIP) peak, a material-intrinsic feature where most secondary particles ex- hibit typical energy loss rates; The apparent downward step is a histogram binning artifact (bin width 0.1 MeV cm2/mg) en- hanced by the logarithmic scale, consistent with the long-tail characteristics of the Landau-Vavilov distribution.

In the figures, when the incident angle increases, the dis- tribution functions entering the GaN sensitive layer are con- sistent in most intervals, with obvious deviations only in the high-LET tail(> 15 MeV cm2/mg), indicating that after pro- tons incident through the drain top, undergoing multiple scat- tering and energy transfer dissipation, the angular effect is significantly smoothed out in the sensitive layer. Compre- hensive analysis shows that at 10 MeV, due to lower pro- ton energy, the average A and Z of secondary particles are minimal (A deviation 9.13% ± 2%, similar for Z), with larger deviations in the high-tail region of the LET spectrum, consistent with the long-tail characteristics of the Landau- Vavilov distribution. As energy increases, the proportion of Z>20 secondary fragments increases from 15% ± 3% at 10 MeV to 40% ± 5% at 200 MeV, the number of high-LET events increases from 0.2% to 1.2% (a 500% increase), and the maximum LET increases from 15 MeV cm2/mg to 18 0204010-910-510-1AdN/dX10 MeV(a)1020Z(b)50100Ek(MeV)(c) 0 Degree 30 Degree 45 Degree 60 Degree110LET(MeV · cm^2/mg)(d)0204010-910-510-1dN/dXA100 MeV(a)1020Z(b)50100Ek(MeV)(c) 0 Degree 30 Degree 45 Degree 60 Degree110LET(MeV · cm^2/mg)(d)

4 Table 2 . Comparison of Average Observables in Three Regions un- der 100 MeV Vertical Incidence ¯A ¯Z Ek(MeV) L ¯ET (cid:0)MeV · cm2/mg(cid:1) Region Gate 14.2 7.1 Drain 16.8 8.4 Fig. 4 [Figure 4: see original paper]. Distributions of A, Z, Ek, and LET (Normalized Counts dN/dX) of Secondary Particles Entering the GaN Sensitive Layer for 200 MeV Protons Incident on the Drain at Different Angles (0 ∘ , 30 ∘ , 45 ∘ , 60 ∘).

Table 1 . Average Mass Number A and Charge Number Z of Sec- ondary Fragments Entering the Sensitive Layer for Protons of 10 MeV, 100 MeV, and 200 MeV Incident on the Drain at Different Angles

200 MeV 0.827 0.313 0.826 0.311 0.824 0.311 0.822 0.309

MeV cm2/mg, which a 20% increase. This trend arises from the increase in proton nuclear reaction cross-sections with en- ergy, consistent with the recoil ion LET limits in GaN, Where 20% higher than Si.

B. Regional Comparative Analysis The 3 tipical region comparison shows that the gate tends toward low-Ek and low-Z distributions under low-energy (10 50 MeV) conditions, for example, average Ek of 35 MeV ± 4 MeV (20% lower than the drain), average Z of 7.1 ± 0.7, due to filtering restrictions from the Au/Ni over- layer and AlGaN barrier, leading to more significant shallow- layer energy loss, consistent with the Z/A dependence in the Bethe-Bloch formula (1) . At 10 MeV, the proportion of high- LET events at the gate is only 3%± 1%, reflecting the energy screening effect of the overlayer. In contrast, the drain has a larger proportion of high-LET events (increase from 10−3 to 1.25$×$10−3, 25% higher than the gate), benefiting from open geometry allowing more high-Z recoils to penetrate, with av- erage Z of 8.4 ± 0.9 and 15% higher standard deviation in Ek distribution. The gap region is intermediate, most sensi- tive to angle changes but with the fastest attenuation,which converges 300 nm, with LET peak between those of the gate and drain,which about 12 MeV cm2/mg.

Table 2 summarizes the average observables in the three regions under 100 MeV vertical incidence. These differences quantify the "gating" effect of overlayer filtering strength on particle composition, highlighting spatial non-uniformity of Fig. 5 [Figure 5: see original paper]. Variations of Average A, Z, Ek (MeV), and LET (MeV cm2/mg) with Energy for 10 500 MeV Protons Vertically Irradiating the Gate Region. regionalized sensitivity compared to overall GaN LET spectra in literature [8], providing microscopic evidence for ex- plaining gate-prone failures such as SEGR.

As shown in Fig. 5 to Fig. 7 [Figure 7: see original paper], as the energy increases, the changes in the four physical quantities across the three re- gions exhibit differences in sensitivity. The gate is the most sensitive. In the 10 50 MeV range, the average A increases from 14.0 to 15.0, which 7%, the average Z from 7.0 to 7.5, which 7% increase, the average Ek from 35 MeV to 45 MeV, which 29% increase, the maximum LET value decreases from

18 MeV cm2/mg to 15 MeV cm2/mg, which 17% decrease,

and the proportion of high-LET intervals increases from 5% to 15%, representing a 200% relative increase. The source- In the 50 200 MeV range, the gate gap is intermediate. changes are similar but with an 18% lower rate and a 22% increase. The drain is the least sensitive. In the 10 50 MeV range, the changes are minimal, with a 4% increase and a 10% decrease; obvious changes occur above 100 MeV, with the high-LET proportion increasing from 8% to 25%. These differences stem from variations in the top materials and layer counts across the regions, affecting the penetration of sec- ondary fragments [20].

C. Discussion The simulation results reveal that the flattening of the angular effect originates from the accumulation of multiple Coulomb scattering (Equation 2), which dominates in thick overlayers and leads to an attenuation of angle dependence exceeding 90% at the depths of the sensitive layer. The en- hancement of high-Z fragments and high-LET events with in-0204010-910-510-1dN/dXA200 MeV(a)1020Z(b)(b)50100Ek(MeV)(c) 0 Degree 30 Degree 45 Degree 60 Degree110LET(MeV $\cdot$ cm^2/mg)(d)0204010-910-510-1dN/dXAGate(a)1020Z(b)50100Ek(MeV) 10 MeV 50 MeV 100 MeV 200 MeV 300 MeV 400 MeV 500 MeV(c)110LET(MeV $\cdot$ cm^2/mg)(d)

5 mechanisms in p-GaN gate structures [7, 13]; the open ge- ometry of the drain allows for broader distributions, match- ing the absence of SEB observations in Cascode GaN HEMT experiments [15]. These microscopic insights bridge simula- tions and experiments, providing a foundation for SEE prob- ability assessments, such as using the proportion of high-LET events to predict threshold degradations [13]. Limitations in- clude the omission of bias electric fields; future work could integrate TCAD simulations to investigate the impact of field-enhanced charge collection on SEB/SEGR.

IV. CONCLUSIONS This paper quantifies the microscopic mechanisms of proton-induced single event effects (SEEs) in GaN HEMTs through Geant4 simulations. The simulation results indi- cate that angular effects are significantly smoothed out in the sensitive layer, with attenuation rates inversely proportional to energy, mainly due to the cumulative effects of multiple Coulomb scattering, resulting in secondary particle distribu- tion differences less than 10%. Energy increase enhances the proportion of high-Z secondary fragments($Z > 20$) and the number of high-LET events, for example, in the drain region, from 10 MeV to 200 MeV, the proportion of high-Z fragments increases from 15% to 40%, and high-LET events increase by 500%, reflecting the amplifying effect of increasing nuclear reaction cross-sections on energy deposition .

Differences in proton incidences across regions further re- veal that overlayer materials and geometric structures dom- inate sensitivity: The Gate is most sensitive to proton en- ergy changes,where, high-LET event proportion increasing of 200%, due to high-Z overlayers screening low-energy parti- cles and amplifying high-energy region recoil ion yields; the source-gate gap is intermediate; the drain is least sensitive, benefiting from open paths allowing broader particle distri- butions. These microscopic patterns bridge particle transport with device-level SEE threshold degradations, for example, high-LET peaks of gate can explain SEB threshold reductions under proton irradiation. Compared to existing work [15], this paper’ s regionalized quantification highlights the key role of overlayers in proton-induced SEEs, providing a physical basis for GaN HEMT radiation-hardened design, such as op- timizing gate overlayers to alleviate energy sensitivity or ad- justing buffer layer thickness to suppress high-LET events.

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Fig. 6 [Figure 6: see original paper]. Variations of Average A, Z, Ek (MeV), and LET (MeV cm2/mg)Values with Energy for 10 500 MeV Protons Verti- cally Irradiating the Source-Gate Gap Region.

Variations of Average A, Z, Ek (MeV), and LET Fig. 7. (MeV cm2/mg) with Energy for 10 500 MeV Protons Vertically Irradiating the Drain Region. creasing energy is associated with the rise in nuclear reaction cross-sections, which explains the reduction in SEB thresh- olds under proton irradiation (such as a 15-20% decline re- ported by Zhang et al.[11]), as the high-LET peaks at the gate exceed the SEGR thresholds, 20 30 MeV cm2/mg. The re- gional differences quantify the filtering strength of the over- layers: the energy screening at the gate amplifies high-LET recoils in the high-energy region, consistent with the SEB [1] A. Ionascut-Nedelcescu, C. Carlone, A. Houdayer et. al. , Radiation hardness of gallium nitride, IEEE Trans. Nucl.

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