

Article

The Study of the Single Event Effect in AlGa_N/Ga_N HEMT Based on a Cascode Structure

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Abstract: An attractive candidate for space and aeronautic applications is the high-power and miniaturizing electric propulsion technology device, the gallium nitride high electron mobility transistor (Ga_N HEMT), which is representative of wide bandgap power electronic devices. The cascode AlGa_N/Ga_N HEMT is a common structure typically composed of a high-voltage depletion-mode AlGa_N/Ga_N HEMT and low-voltage enhancement-mode silicon (Si) MOSFET connected by a cascode structure to realize its enhancement mode. It is well known that low-voltage Si MOSFET is insensitive to single event burnout (SEB). Therefore, this paper mainly focuses on the single event effects of the cascode AlGa_N/Ga_N HEMT using technical computer-aided design (TCAD) simulation and heavy-ion experiments. The influences of heavy-ion energy, track length, and track position on the single event effects for the depletion-mode AlGa_N/Ga_N HEMT were studied using TCAD simulation. The results showed that a leakage channel between the gate electrode and drain electrode in depletion-mode AlGa_N/Ga_N HEMT was formed after heavy-ion striking. The enhancement of the ionization mechanism at the edge of the gate might be an important factor for the leakage channel. To further study the SEB effect in AlGa_N/Ga_N HEMT, the heavy-ion test of a cascode AlGa_N/Ga_N HEMT was carried out. SEB was observed in the heavy-ion irradiation experiment and the leakage channel was found between the gate and drain region in the depletion-mode AlGa_N/Ga_N HEMT. The heavy-ion irradiation experimental results proved reasonable for the SEB simulation for AlGa_N/Ga_N HEMT with a cascode structure.

Keywords: AlGa_N/Ga_N HEMT; cascode structure; single event effects; technology computer-aided design simulation; heavy-ion irradiation experiment



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1. Introduction

As high-power and miniaturizing electric propulsion technology devices continue to develop, high-performance and high-reliability wide bandgap power electronic devices begin to play an important role in air and space vehicles. Gallium nitride high electron mobility transistors (Ga_N HEMT) are representative of wide bandgap power electronic devices and could be an attractive candidate for space and aeronautic applications due to their excellent electrical characteristics, such as high electron mobility, high breakdown voltage, and high thermal conductivity. To realize space and aeronautic applications, the radiation effect should be considered, including the total ionizing dose (TID) effect, single event effect (SEE), and the displacement damage dose (DDD) effect. Due to the existence of two-dimensional electron gas (2DEG), AlGa_N/Ga_N HEMT, fabricated on AlGa_N/Ga_N heterojunction, is in depletion mode. To ensure the reliability of the device in space applications, enhancement-mode devices can be adopted. The enhanced mode is mainly realized in AlGa_N/Ga_N HEMT by the following: p-Ga_N [1,2], F ion implantation [3,4], MIS HEMT [5,6], and cascode structure [7,8]. The total ionizing dose and displacement damage effect on Ga_N HEMT have been studied by many researchers [9–14]. Because there

is no gate dielectric layer in AlGa_N/Ga_N HEMT, Ga_N HEMT is less sensitive to the TID effect. Additionally, some references [12,13] have shown that the DDD effect impacts the direct-current (DC) characteristics of the AlGa_N/Ga_N HEMTs and the failure mechanisms have been basically studied. However, as one of the most important effects of space environment radiation, many studies focused on the enhancement-mode AlGa_N/Ga_N HEMT based on the p-Ga_N structure [15–17]. The SEE characteristics and AlGa_N/Ga_N HEMT failure mechanisms based on the cascode structure are not clear. Therefore, in this paper, we focused on studying the SEE of the AlGa_N/Ga_N HEMTs and analyzing the failure mechanism of the single event burnout (SEB) effect.

To study the radiation response and failure mechanism of the SEB effect for Ga_N HEMTs, TCAD simulation and heavy-ion irradiation experiments were carried out. The remainder of the paper is organized as follows.

Firstly, according to the circuit structure shown in Figure 1, the cascode structure of AlGa_N/Ga_N HEMT, including the depletion-mode AlGa_N/Ga_N HEMT and Si MOSFET, were modeled. Because low-voltage Si MOSFET is not sensitive to the SEB effect, we focused on studying the SEE in the depletion-mode AlGa_N/Ga_N HEMT. The simulation results showed that (1) the SEB effect of the AlGa_N/Ga_N HEMT was influenced by heavy-ion energy and track position. Further, (2) a leakage channel between the gate electrode and drain electrode was observed after heavy-ion striking in depletion-mode AlGa_N/Ga_N HEMT.

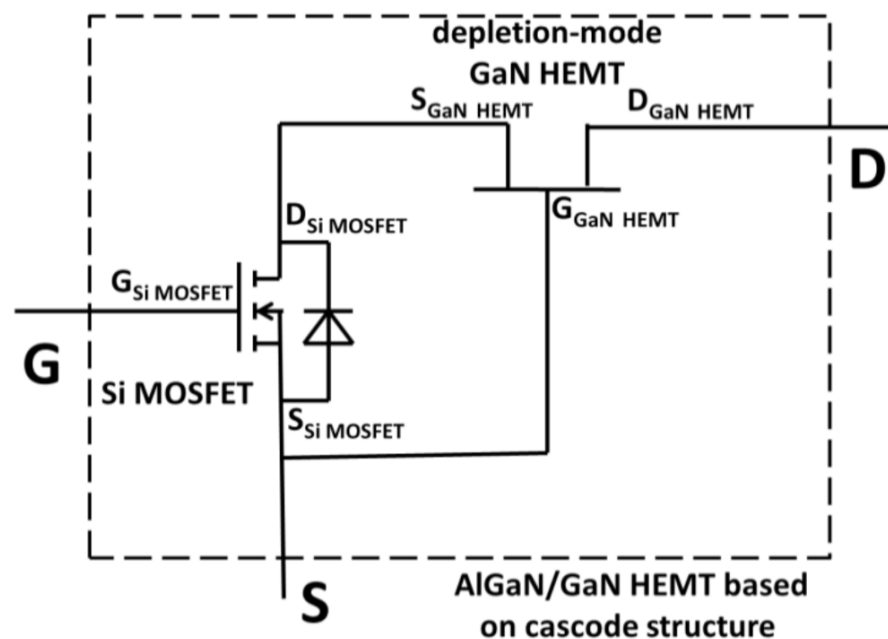


Figure 1. The schematic of aluminium gallium nitride /gallium nitride high electron mobility transistor (AlGa_N/Ga_N HEMT), based on the cascode structure.

Heavy-ion irradiation experiments of the commercial cascode AlGa_N/Ga_N HEMT were conducted in an off-mode condition. The experimental results showed that (1) the depletion-mode AlGa_N/Ga_N HEMT was burnt out under $V_{ds} = 50$ V for Ge ions at LET = 28.5 MeV·cm²/mg (about 0.31 pC/μm). Moreover, it showed (2) a leakage channel between the gate electrode and the drain electrode in the depletion-mode, where AlGa_N/Ga_N HEMT was formed after the heavy-ion striking.

Finally, the possible SEE failure mechanism was proposed. We proved that the enhancement of the impact ionization mechanism at the edge of the gate might be an important factor in the formation of the leakage channel.

2. Simulation Results and Discussion

As shown in Figure 1, a high voltage depletion-mode AlGaIn/GaN HEMT and a low voltage enhancement-mode silicon (Si) MOSFET were connected to form a high voltage enhancement-mode AlGaIn/GaN HEMT in the cascode structure. For the cascode AlGaIn/GaN HEMT circuit, the drain electrode of GaN HEMT served as the drain port and the gate electrode of Si MOSFET acted as the gate port. The source port of the device was formed by connecting the source electrode of Si MOSFET and the gate electrode of GaN HEMT. It is well known that the low voltage power MOSFETs are robust to the SEB effect [18–20]. Therefore, to investigate the mechanism of the SEB induced by heavy ion irradiation on cascode AlGaIn/GaN HEMT, we studied the SEB effect of the depletion-mode AlGaIn/GaN HEMT. TCAD simulation was carried out with the Sentaurus TCAD simulator.

2.1. Modeling

In the simulation, the generic model of the depletion-mode AlGaIn/GaN HEMT supported by the foundry was adopted. According to previous reports [21–23], the architecture considered in the simulation is shown in Figure 2. The structure consisted of a Si substrate, a GaN buffer layer, an unintentional doped GaN channel layer, an unintentional doped AlGaIn barrier layer, and a SiN passivation layer. The breakdown voltage of the simulated device was higher than 900 V. The breakdown, transfer, and output characteristics of the simulated structure are shown in Figure 3. The threshold voltage (V_{th}) of the AlGaIn/GaN HEMT was approximately -2.5 V.

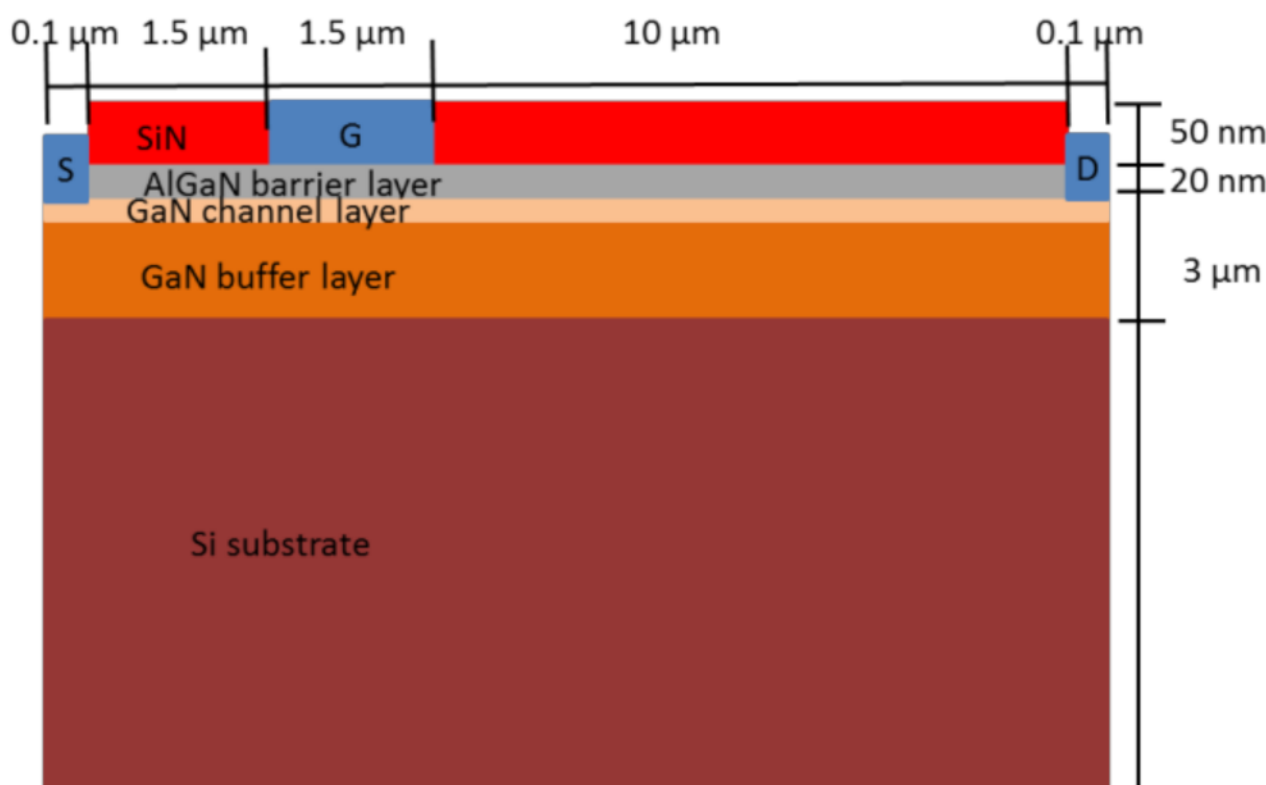


Figure 2. The schematic of the depletion-mode AlGaIn/GaN HEMT.

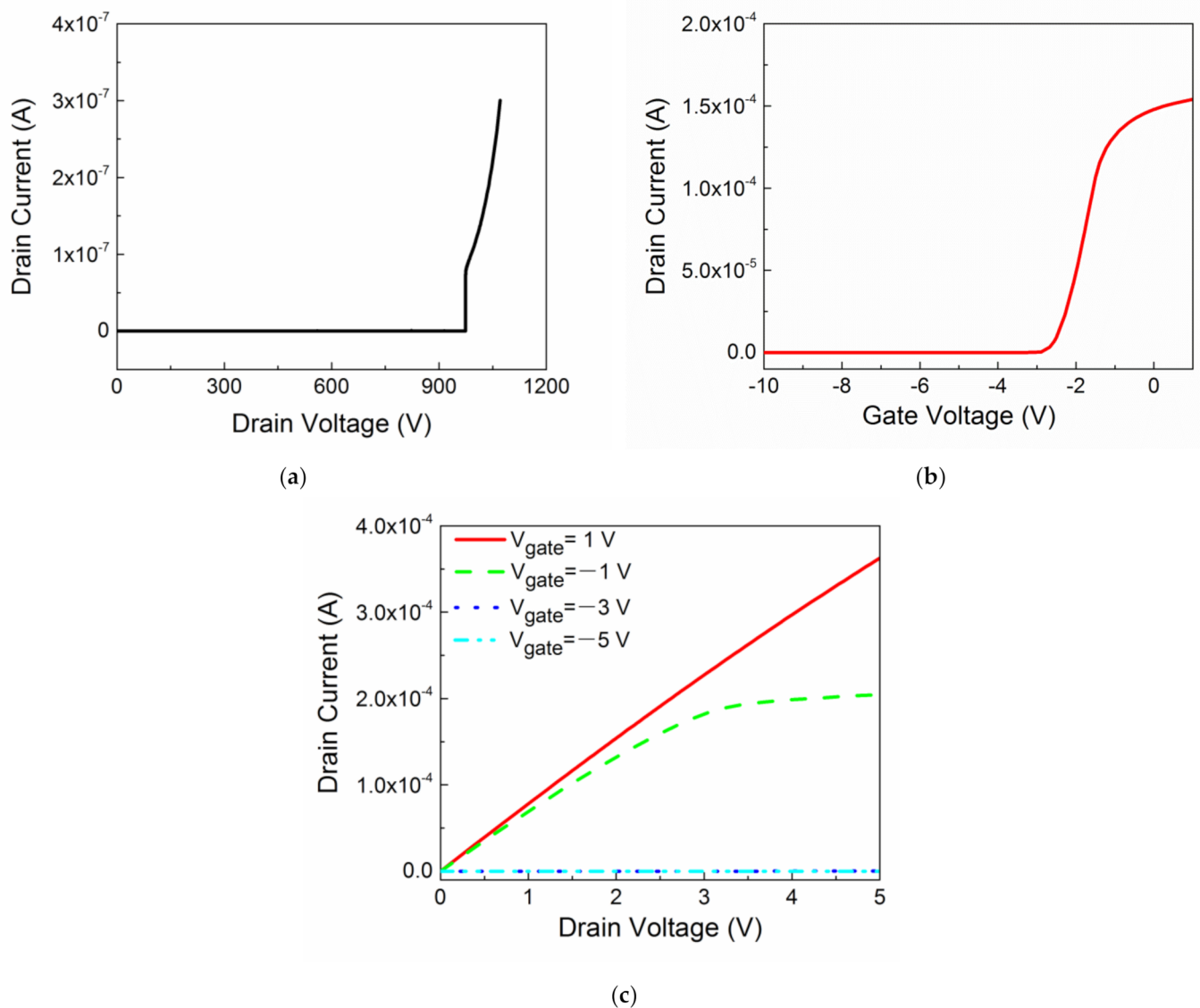


Figure 3. The characteristics of the depletion-mode AlGaIn/GaN HEMT: (a) the breakdown characteristic, (b) the transfer characteristic, and (c) the output characteristics.

In the simulation, we used a heavy-ion model in Sentaurus software. The impact ionization model and drift-diffusion model were adopted. To simplify the simulation process, thermal equations (lattice heating) were not considered in this paper. The heavy-ion was vertical incidence on the device from the front side. The Gaussian track radius was 20 nm spatially.

2.2. Simulation Results and Discussion

2.2.1. SEB Characteristics of HMET

To trigger the device's SEE effect, we adopted a track length of 10 μm and linear energy transfers (LET) of 1 pC/ μm . The drain, source, and gate port of the depletion-mode AlGaIn/GaN HEMT were biased at 400 V, 10 V, and 0 V, respectively ($V_{gs} = -10$ V, $V_{ds} = 390$ V), which ensured that the device was in the off state. The transient drain, source, and gate currents are presented in Figure 4. The currents increased immediately after a heavy-ion struck the device. The drain current increased to about 2.5 mA, the gate current increased to about 1.5 mA, and the source current increased to about 1 mA. Approximately 1 ns after striking, the source current returned to 0.1 μA and the drain current and gate current reached 0.2 mA. The drain current and gate current were about 0.1 mA at 50 ns

after striking. This indicated that a leakage channel between the gate electrode and the drain electrode in depletion-mode AlGaIn/GaN HEMT was formed.

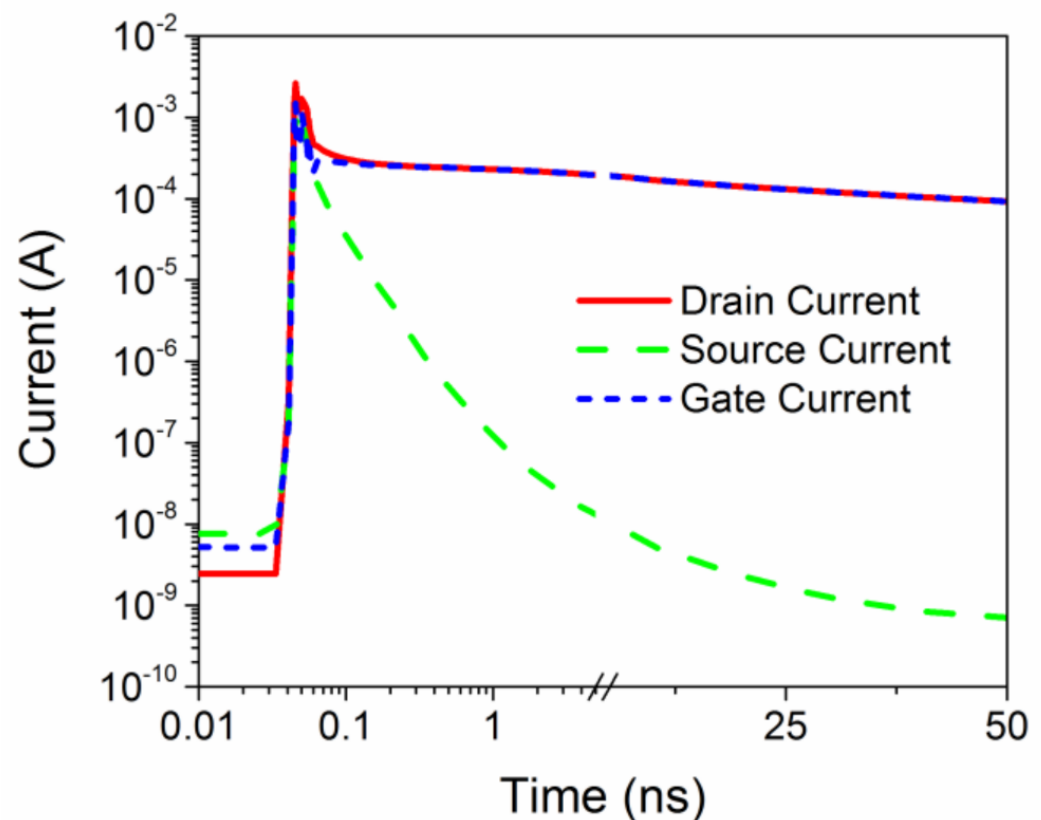


Figure 4. The transient drain, source, and gate currents after heavy-ion striking.

2.2.2. Influence Factors of SEB

- Heavy-ion energy

Heavy-ion energy, heavy-ion track length, and heavy-ion track position are important parameters that affect the single event effect of the depletion-mode AlGaIn/GaN HEMT. Heavy-ion energy is related to the electron-hole pairs produced in the device. To study the influence of heavy-ion energy on the SEE of the depletion-mode AlGaIn/GaN HEMT, simulation experiments with different LETs (10, 5, 1, 0.1, 0.01, 0.005, 0.001 pC/ μ m) were carried out. The track length (10 μ m) and track position (close to the drain electrode) were adopted in the simulation. The transient drain currents after heavy ion impacts for different LETs were shown in Figure 5. The transient drain current increased with the LET increasing and reached a saturation value until the LET was higher than 0.1 pC/ μ m. It indicated that the electron-hole pairs generated in the AlGaIn and GaN layers increased with the LET grew and reached the maximum at 0.1 pC/ μ m [16].

- Heavy-ion track length

In addition to heavy-ion energy, the heavy-ion track length is also an important parameter. The impacts of heavy-ion with different track lengths were also studied. In the simulation, the heavy-ion energy (1 pC/ μ m) and track position (close to the drain electrode) were adopted and the track lengths were 2, 5, 10, and 15 μ m. The transient drain currents after heavy ion impacts for different track lengths were shown in Figure 6. The amplitude of transient drain current almost kept constant under these simulation conditions. In these simulation conditions, the heavy-ion had passed through the GaN channel layer and reached the GaN buffer layer or the Si substrate layer. In other words, the heavy-ion had passed through the active region of the depletion-mode AlGaIn/GaN HEMT. Therefore, the

transient drain currents did not change with heavy-ion track length under these simulation conditions. These results indicated when the heavy-ion passed through the GaN channel layer and reached the GaN buffer layer, the heavy-ion track length had little effect on the SEE of the depletion-mode AlGaIn/GaN HEMT.

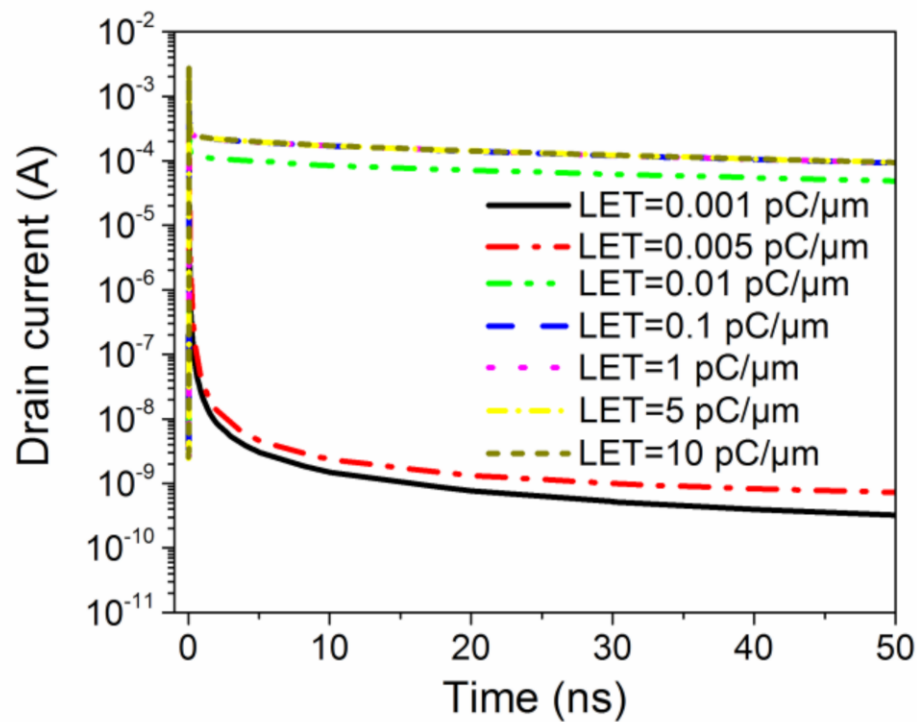


Figure 5. The transient drain currents after heavy-ion striking with different linear energy transfers (LETs).

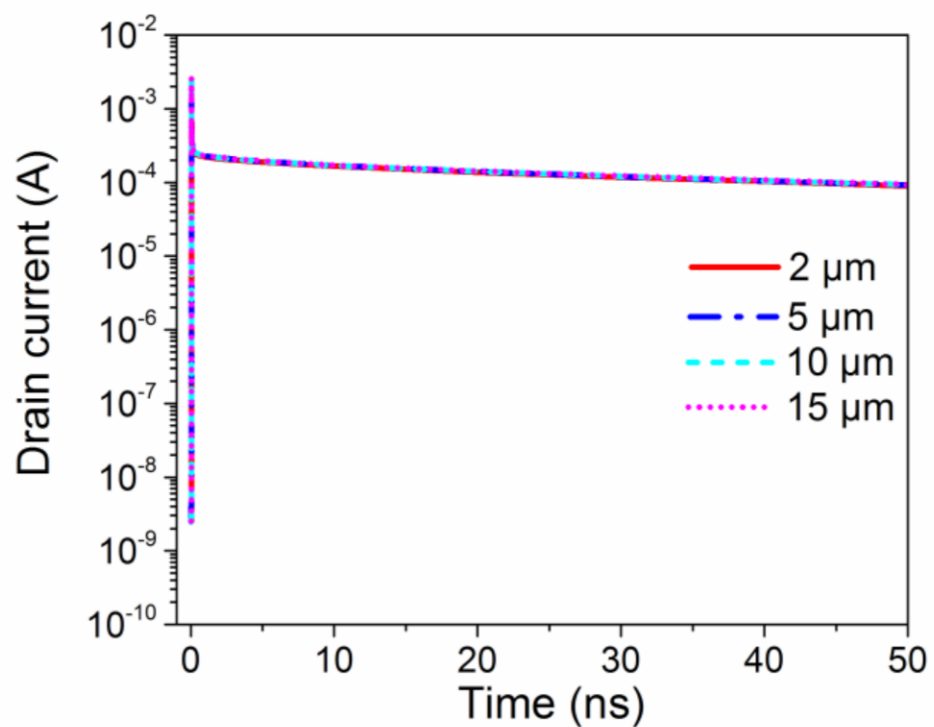


Figure 6. The transient drain currents after heavy-ion striking with different track lengths.

- Sensitive region of SEB

To localize the sensitive region of the depletion-mode AlGaIn/GaN HEMT, different track positions of heavy-ion were studied. The heavy-ion energy ($1 \text{ pC}/\mu\text{m}$) and track length ($10 \mu\text{m}$) were adopted in the simulation. The schematic of heavy-ion tracks on the depletion-mode AlGaIn/GaN HEMT is revealed in Figure 7. The transient drain currents after heavy-ion impact on different track positions are shown in Figure 8. The drain currents were about 0.1 mA at 50 ns after the heavy-ions striking at P7, P8, and P9, while the drain currents were lower than 10^{-8} A at 50 ns after the heavy-ions striking at P1 to P6. These indicated that a SEB current was triggered when the heavy-ion impact on the location of P7, P8, and P9. Moreover, the closer the track position is to the drain region, the more sensitive it is to the SEB device.

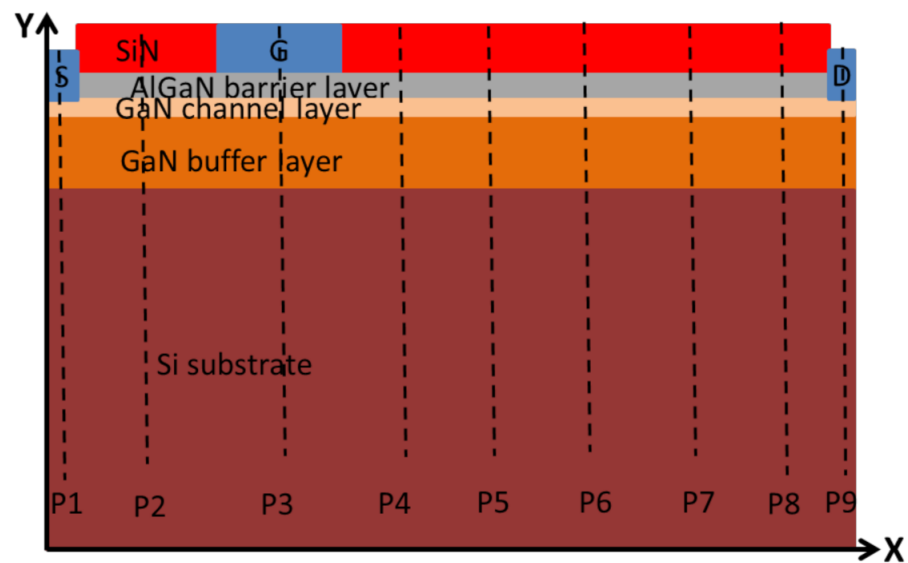


Figure 7. The cross-section of AlGaIn/GaN HEMT with different heavy-ion track positions.

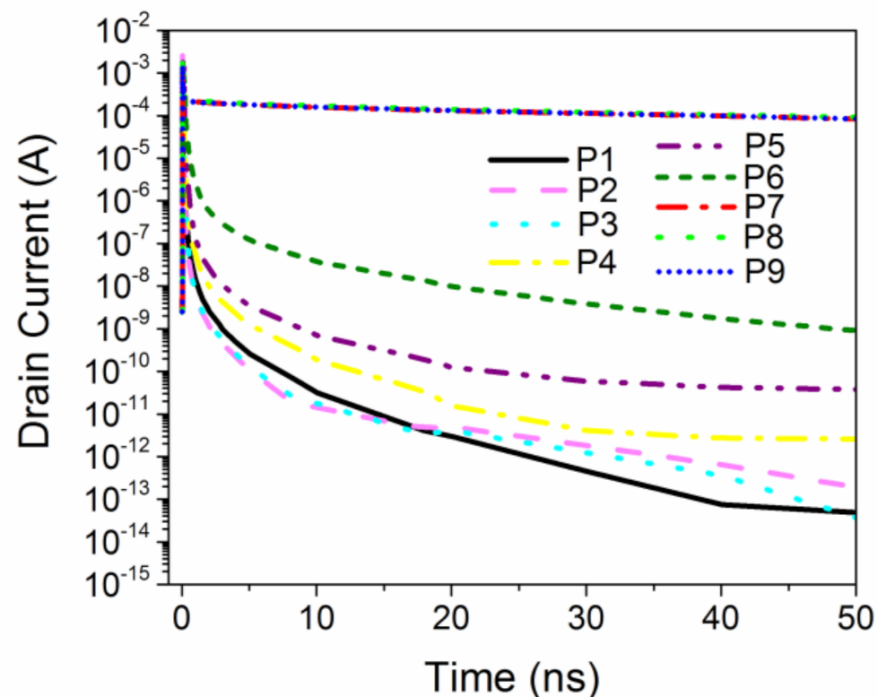


Figure 8. The transient drain currents after heavy-ion striking with different positions.

2.2.3. The Failure Mechanism of SEB

To understand the SEB mechanism, the cross-sections of the total current density after the heavy-ion impact on location P5 and P8 are shown in Figures 9 and 10, respectively. Figures 9a and 10a show the initial states of the total current density before the heavy-ions striking. Figures 9b and 10b show the total current density after the heavy-ions striking at P5 and P8 for 0.05 ns. After the heavy-ions striking, the total current density in the GaN buffer layer increased (from green to orange), indicating that the GaN buffer layer forming a leakage channel. Figures 9c and 10c show the total current density after the heavy-ions strike at P5 and P8 for 50 ns. These showed that the leakage channel disappeared at 50 ns after the heavy-ions striking at P5, while it was still a leakage channel at 50 ns after the heavy-ions striking at P8.

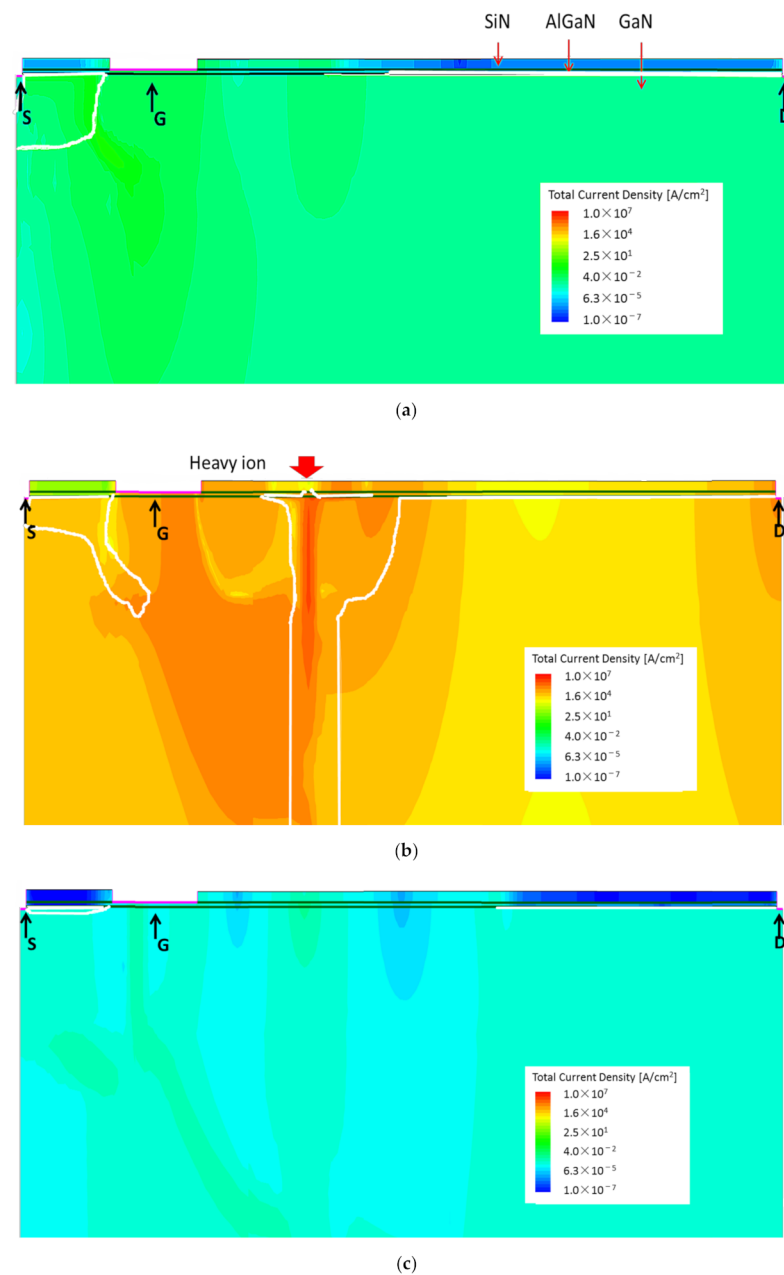


Figure 9. The cross-sections of the total current density with time after the heavy-ion striking at P5: (a) before heavy-ion striking, (b) 0.05 ns after heavy-ion striking, and (c) 50 ns after heavy-ion striking. The white line represented the depletion region.

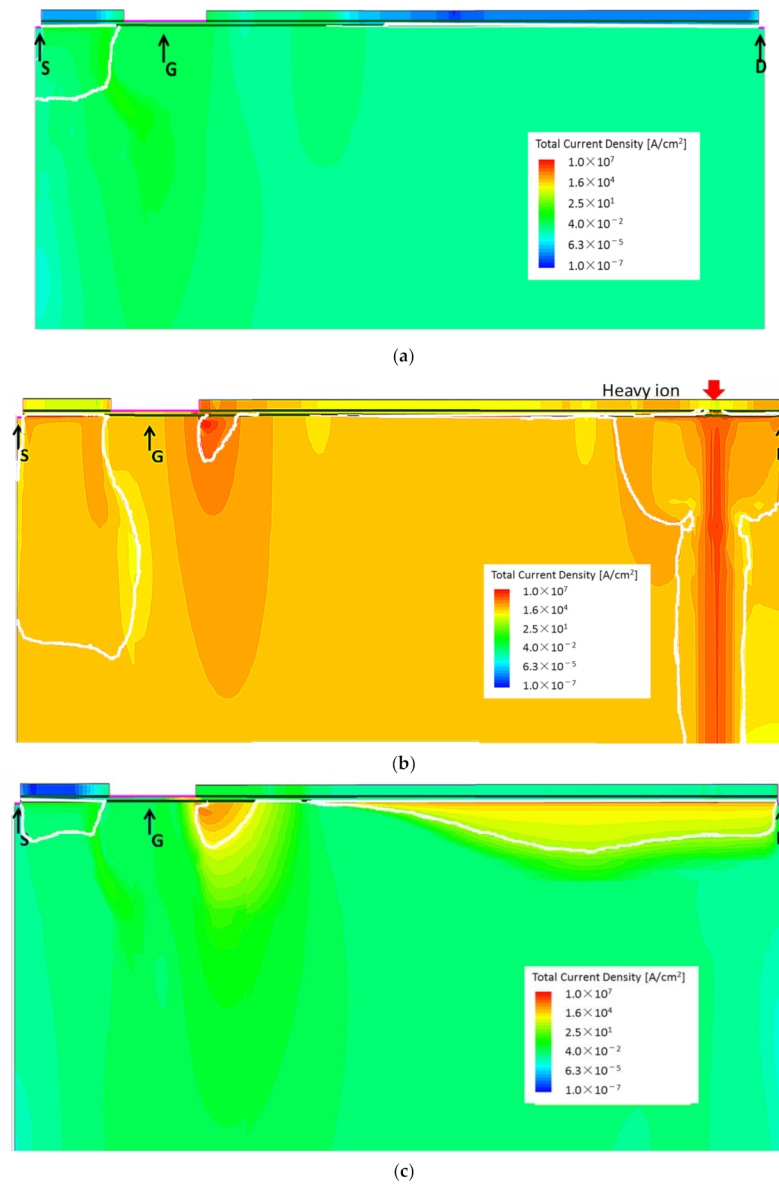


Figure 10. The cross-sections of the total current density with time after heavy-ion striking at P8: (a) before heavy-ion striking, (b) 0.05 ns after heavy-ion striking, and (c) 50 ns after heavy-ion striking. The white line represented the depletion region.

After the heavy-ions strike the device, the electron-hole pairs were generated. Electrons flowed toward the drain under the high drain voltage and collected by the drain electrode. Holes were left in the GaN buffer layer, leading to the electrons injection of the source and gate electrode [16,24]. Thus, the large transient current was generated in the source, gate, and drain regions. The leakage channel of the GaN buffer layer was formed. The electron-hole pairs generated by heavy-ions decreased with time, leading to the leakage current reduced.

In order to further understand the SEB mechanism, the cross-sections of the impact ionization after the heavy-ion striking at P5 and P8 were studied. Figures 11a and 12a were the initial value of the impact ionization before the heavy-ions struck. Figure 11b,c and Figure 12b,c show the impact ionization at 0.05 ns and 50 ns after the heavy-ions striking at P5 and P8. As shown in Figure 11, after the heavy-ions striking at P5, the impact ionization at the edge of the gate region decreased at 0.05 ns and the value was still low at 50 ns. As shown in Figure 12, after the heavy-ions striking at P8, the impact ionization at the edge of the gate region and the drain region increased at 0.05 ns and the value was still

high at 50 ns. The electron-hole pairs were generated after the heavy-ion injected to the AlGaIn/GaN HEMT. Then the generated electron-hole pairs drifted under the applied voltage. Electrons flowed toward the drain under the high drain voltage and collected by the drain electrode. Holes were left in the GaN buffer layer, leading to the electrons injection of the source, and gate electrode. The movement of the electron-hole pairs led to the changing of the potential distribution. When the heavy-ions struck at P5, which was close to the gate electrode, the electrons were injected from the source and gate electrode quickly. This process decreased the potential near the drain, which decreased the impact ionization at the edge of the gate region. When the heavy-ions struck at P8, which was close to the drain electrode, electrons were quickly collected by the drain and holes left in the GaN buffer layer accumulated. This process increased the potential near the drain, which enhanced the impact ionization at the edge of the gate region. The enhancing impact ionization increased the number of generated carriers, which increased the probability of electron tunneling of the gate region. This might be attributed to the burnout of the gate electron of the AlGaIn/GaN HEMT after heavy-ion striking at P8.

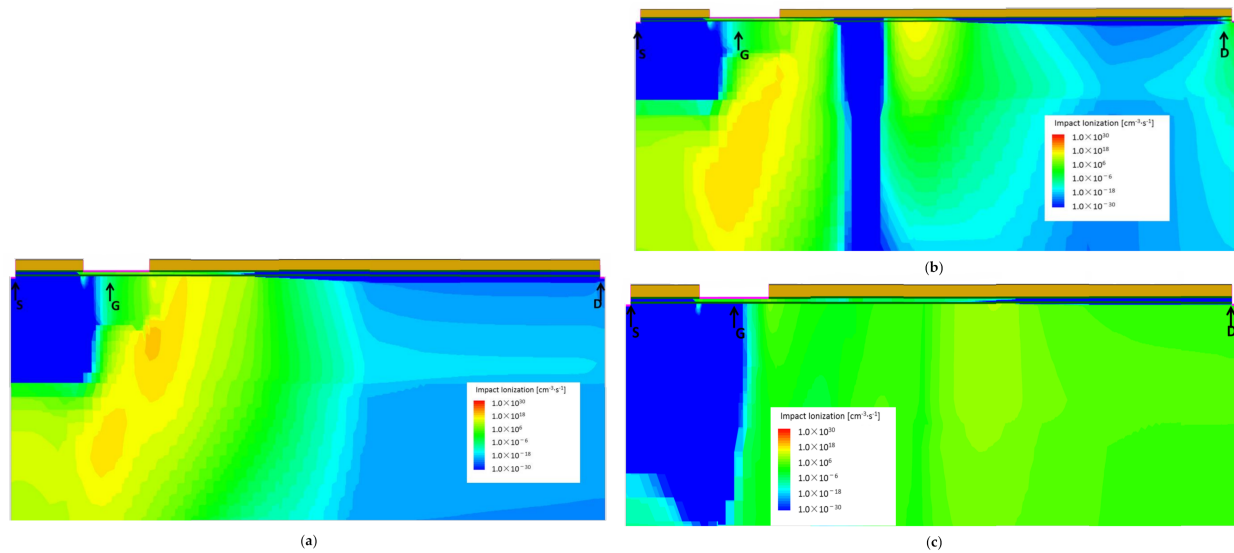


Figure 11. The cross-sections of the impact ionization after the heavy-ion striking at P5: (a) before heavy-ion striking, (b) 0.05 ns after heavy-ion striking, and (c) 50 ns after heavy-ion striking.

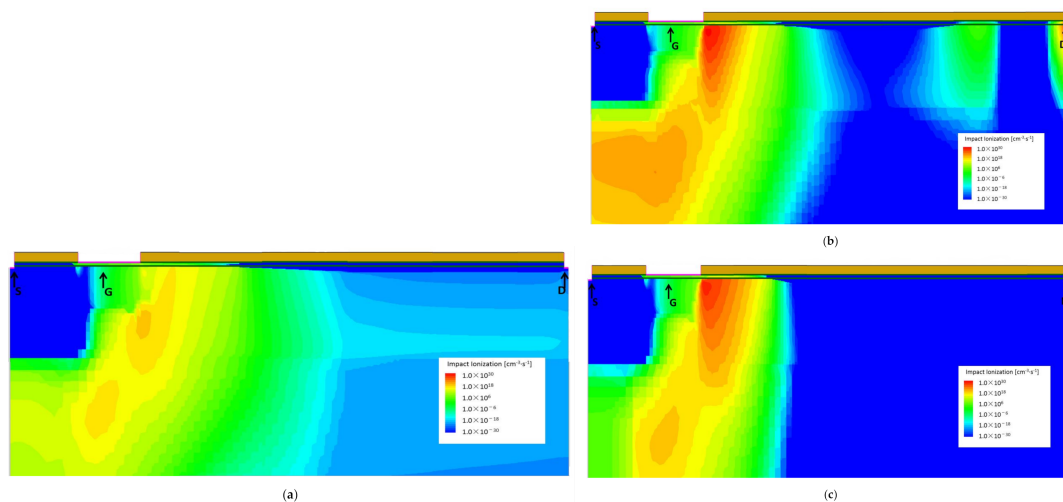


Figure 12. The cross-sections of the impact ionization after the heavy-ion striking at P8: (a) before heavy-ion striking, (b) 0.05 ns after heavy-ion striking, and (c) 50 ns after heavy-ion striking.

3. Heavy-Ion Experimental Results and Discussion

3.1. Experiment Samples and Setup

To further study the phenomenon of the drain current increase obtained in the simulation section, a commercial GaN HEMT with a breakdown voltage of 900 V was chosen. The devices under test (DUTs) were commercial devices employing a cascode structure from transform (TP90H180PS). The radiation experiments were carried out on the heavy-ion accelerator of China Atomic Energy Research Institute, shown in Figure 13. In the heavy-ion radiation experiments, the device was biased at the off state. The source port and gate port were grounded ($V_{gs} = 0$ V). The drain port was biased at 50 V ($V_{ds} = 50$ V). The heavy-ion parameters used in the irradiation experiment are shown in Table 1. For the heavy-ion irradiation with the flux of about 10^4 particle/cm²/s, the devices were irradiated to the fluence of 5×10^6 particle/cm². The drain currents were monitored by Keithley 2470 during the heavy-ion irradiation. The drain current and gate current were measured by Keithley 2470 and 2450 after heavy-ion irradiation.

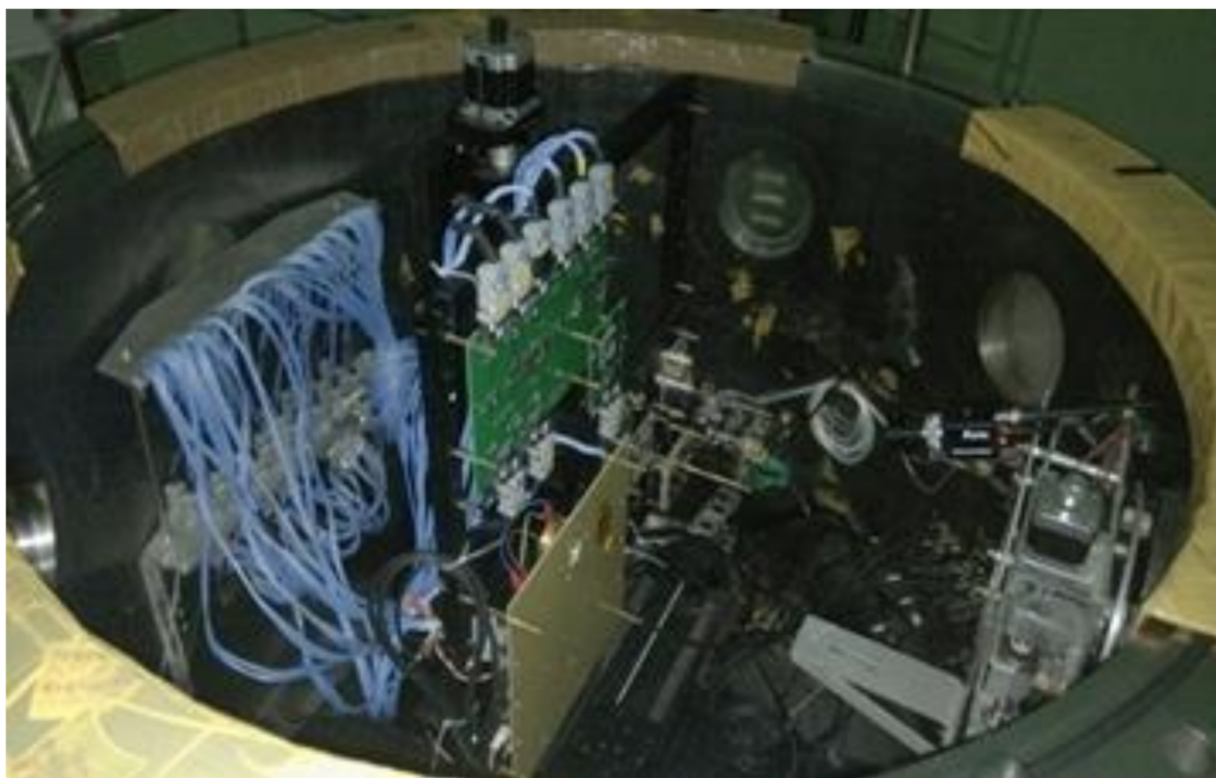


Figure 13. The heavy-ion accelerator of China Atomic Energy Research Institute.

Table 1. Heavy ions used in the experiment.

Heavy-Ion	Energy (MeV)	LET(GaN) (MeV·cm ² /mg)	Strike in GaN (μm)
⁷⁴ Ge ^{11,20+}	210	28.5	16.21

3.2. Experiment results and discussion

The transient drain currents during the heavy-ion irradiation are shown in Figure 14. When the drain port was biased at 50 V, the drain current quickly increased to 10 mA (current limitation), which took about 45 s at LET = 28.5 MeV·cm²/mg (about 0.31 pC/μm).

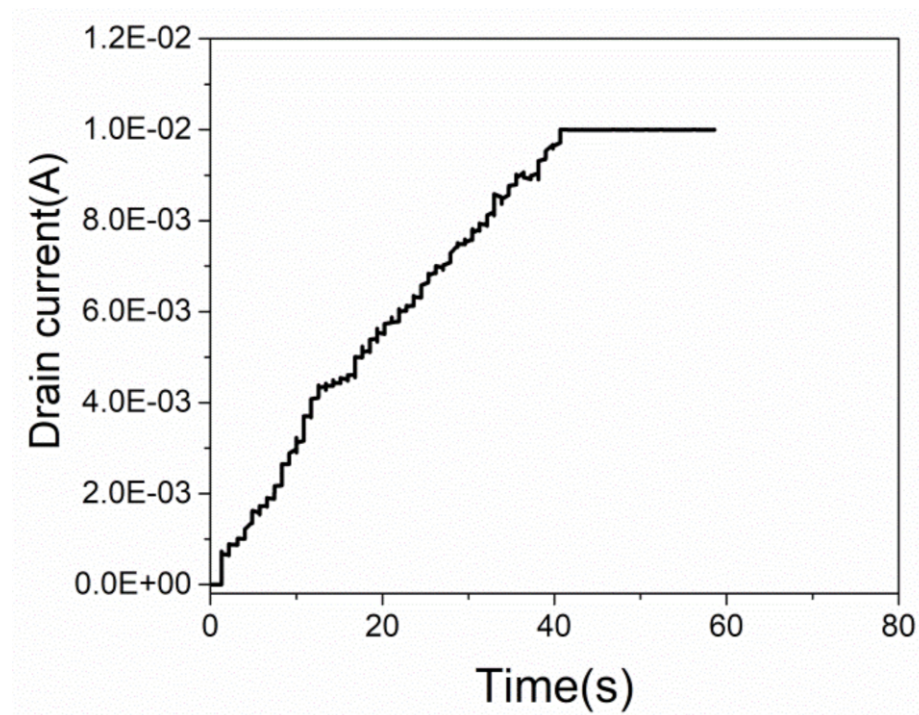


Figure 14. The drain currents of the device at $V_{ds} = 50$ V for Ge ions at LET = $28.5 \text{ MeV} \cdot \text{cm}^2/\text{mg}$ (about $0.31 \text{ pC}/\mu\text{m}$).

After heavy-ion irradiation, the drain current and gate current were measured ($V_{gs} = 0$ V), as shown in Figure 15. The drain leakage current increased to approximately 5 mA and the gate leakage current was less than 5 nA at $V_{ds} = 20$ V, $V_{gs} = 0$ V. It indicated that a leakage channel was formed between the source port and drain port in the Cascode AlGaIn/GaN HEMTs. Analyzing from Figure 1, the source port and drain port of the Cascode AlGaIn/GaN HEMTs corresponded to the gate electrode and the drain electrode of the depletion-mode AlGaIn/GaN HEMT. Therefore, a leakage channel was formed between the gate electrode and the drain electrode in the depletion-mode AlGaIn/GaN HEMT.

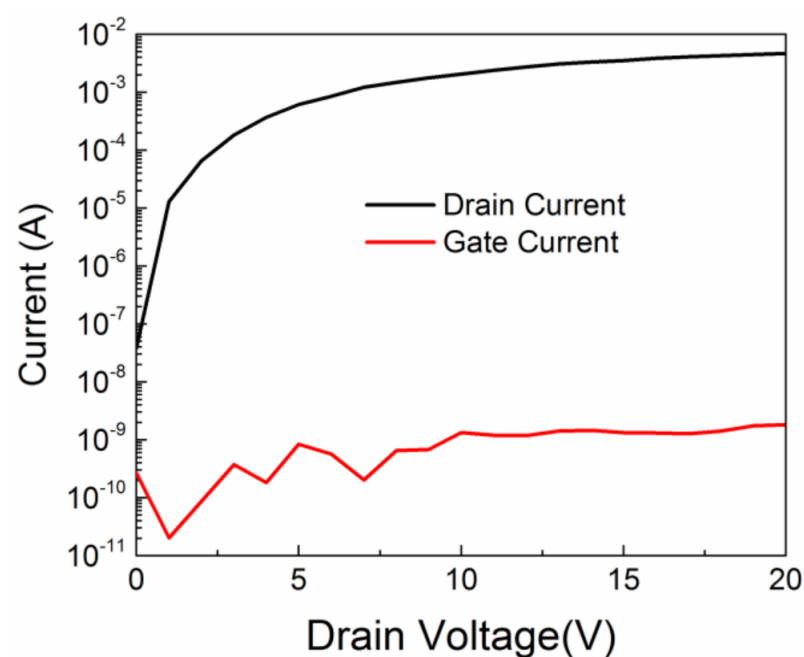


Figure 15. The gate and drain currents of the device after heavy-ion irradiation.

The picture of the DUT before and after heavy-ion irradiation is shown in Figure 16. Figure 16a shows the structure of the cascode AlGaIn/GaN HEMT under test and Figure 16b shows a picture of the device after heavy-ion irradiation. The left device was the low voltage enhancement-mode Si MOSFET and the right device was the high voltage depletion-mode AlGaIn/GaN HEMT. As shown in Figure 16b, the depletion-mode AlGaIn/GaN HEMT was burnt out under $V_{ds} = 50$ V for Ge ions at $LET = 28.5$ MeV·cm²/mg (about 0.31 pC/μm). The Si MOSFET was not sensitive to SEB. Moreover, it was found that the burned area of the depletion-mode AlGaIn/GaN HEMT was located at the gate electrode of the device, using layout photographing technology. A burnout area between the drain and gate was found on the surface of depletion-mode AlGaIn/GaN HEMT from the heavy-ion experimental results, as shown in Figure 16b, which indicated the sensitive region was between the drain electrode and gate electrode.

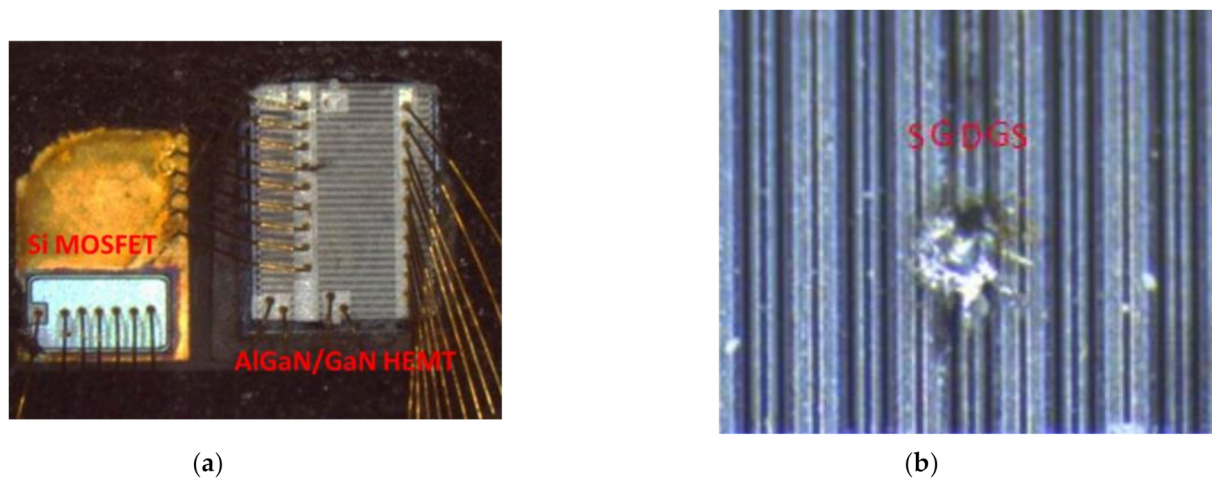


Figure 16. (a) The cascode AlGaIn/GaN HEMT under test and (b) the picture of the device after heavy-ion irradiation.

Analyzing from the simulation results, the sensitive region of the depletion-mode AlGaIn/GaN HEMT was located near the drain. As shown in Figure 16b, the sensitive region was between the drain electrode and gate electrode. The results of the heavy-ion experiment proved reasonable of the SEB simulation for AlGaIn/GaN HEMT with the cascode structure. In a word, the simulation and heavy-ion experimental results both indicated that a leakage channel between the gate electrode and the drain electrode in depletion-mode AlGaIn/GaN HEMT was formed after the heavy-ion striking. This may be the main failure mechanism leading to the SEB effect.

4. Conclusions

Single event effects on cascode AlGaIn/GaN HEMT were studied in this paper. To figure out the mechanism of single event effects, the simulation and experiment were carried out. The simulation results showed that the heavy-ion energy and track position influenced the SEB effect of the depletion-mode AlGaIn/GaN HEMT. When the heavy-ion passed through the GaN channel layer and reached the GaN buffer layer, the heavy-ion track length had little effect on the SEE of the depletion-mode AlGaIn/GaN HEMT. The sensitive region of the depletion-mode AlGaIn/GaN HEMT was located near the drain. When the depletion-mode AlGaIn/GaN HEMT was biased at $V_{gs} = -10$ V and $V_{ds} = 390$ V, heavy-ion ($LET = 0.1$ pC/μm) struck near the drain and caused a leakage current between the gate electrode and drain electrode in the depletion-mode AlGaIn/GaN HEMT. Moreover, the heavy-ion irradiation experiments of a commercial cascode AlGaIn/GaN HEMT (TP90H180PS) were carried out. Experimental results showed that the drain current of the device increased to 10 mA (limiting by the instrument), which was about 45 s at $LET = 28.5$ MeV·cm²/mg (about 0.31 pC/μm) with $V_{ds} = 50$ V. Analyzing from the cascode structure, the leakage channel was formed between the gate electrode and the

drain electrode in the depletion-mode AlGaIn/GaN HEMT. The picture of the DUT after heavy-ion irradiation indicated that the burning area was between the gate electrode and the drain electrode of the depletion-mode AlGaIn/GaN HEMT. The results of the heavy-ion experiment proved reasonable for the SEB simulation of AlGaIn/GaN HEMT with cascode structure. The enhancement of the impact ionization at the edge of the gate was revealed using simulation and it might be an important factor for SEB effect. It was very useful for the radiation-hardened technique for GaN HEMT design.

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

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