Long-term reliability of gate-oxide in Cascode GaN power devices under proton irradiation with different energies

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Abstract

Gallium nitride (GaN)-based devices are highly attractive candidates for space and aeronautics due to their wide band gap and high critical electric field. However, the mechanism of radiation damage and long-term application reliability of the device are still unclear. This study systematically examines the degradation mechanisms of gate oxide layers in Cascode GaN power devices under proton irradiation at different energy levels. The typical degradation of electrical properties was observed. Following 25 MeV proton irradiation, the gate leakage current increased from 4.18$×10−12Ato4.42×10−10A.After60MeVprotonirradiation,thegateleakagecurrentrosefrom3.88×10−12Ato3.81×$10-10 A. In contrast, no significant change in gate current was observed after 100 MeV proton irradiation. Time-dependent dielectric breakdown (TDDB) analysis confirmed an elevated risk of gate current leakage under proton irradiation. Proton irradiation increases defect density in the device oxide layer, leading to the formation of leakage paths. In addition, SRIM simulation results based on Monte Carlo indicated that the interaction cross section between low-energy protons and target nuclei is larger, which will cause more defects in the device, leading to the low-energy proton damage becoming more severe. These radiation-induced defects in the gate oxide layer accelerate dielectric breakdown, ultimately compromising the device' s long-term reliability.

Full Text

Preamble

Long-Term Reliability of Gate Oxide in Cascode GaN Power Devices Under Proton Irradiation with Different Energies

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This paper investigates the effects of proton irradiation at different energies on the long-term reliability of gate oxides in Cascode-enhanced GaN power devices. Typical degradation of electrical properties was observed following irradiation. After 25 MeV proton irradiation, the gate leakage current increased from 4.18×10^{-12} A to 4.42×10^{-10} A. Following 60 MeV proton irradiation, the gate leakage current rose from 3.88×10^{-12} A to 3.81×10^{-10} A. In contrast, no significant change in gate current was observed after 100 MeV proton irradiation. Time-dependent dielectric breakdown (TDDB) analysis confirmed an elevated risk of gate current leakage under proton irradiation. Proton irradiation increases defect density in the device oxide layer, leading to the formation of leakage paths. Additionally, SRIM simulation results based on Monte Carlo methods indicated that the interaction cross-section between low-energy protons and target nuclei is larger, which generates more defects in the device and makes low-energy proton damage more severe. These radiation-induced defects in the gate oxide layer accelerate dielectric breakdown, ultimately compromising the device' s long-term reliability.

Keywords: Proton irradiation, Cascode GaN power devices, Long-term reliability, TDDB, Monte Carlo simulation

Introduction

With the continuous development of high-power electric propulsion technology for space systems and satellite platforms, devices featuring high-frequency, high-power, high-temperature, high-voltage, and radiation-resistant capabilities have gradually become the direction for developing high-efficiency power electronics systems [1-5]. As a typical representative of third-generation wide-bandgap semiconductors, GaN materials possess outstanding characteristics such as a wide bandgap (3.4 eV), high breakdown electric field (5×10^6 V/cm), and strong radiation resistance (10^{10} rad). These intrinsic advantages position GaN-based power devices as premier candidate technologies for space power systems [6-13]. Consequently, investigating the long-term reliability of GaN devices under space radiation environments has become a research priority.

Electronic devices operating in aerospace applications inevitably suffer damage from energetic particles in complex radiation environments [14-16]. Among these, protons constitute the most prevalent particles in space radiation, characterized by high energy and fluence, posing significant threats to onboard electronics [17-19]. Due to the high bond strength of N-Ga and N-Al in GaN HEMT devices, the resulting compounds such as GaN, AlN, and AlGaN exhibit high stability, which yields a high displacement damage energy threshold (19-25 eV). Additionally, the two-dimensional electron gas (2DEG) in GaN is insensitive to defects, so GaN power devices demonstrate strong resistance to displacement damage [17, 18]. GaN has a wide bandgap and theoretically exhibits excellent resistance to ionizing radiation. However, in practice, GaN materials contain a high density of defects, and current GaN devices have stringent process requirements. These factors pose significant challenges to the radiation resistance characteristics of GaN power devices. Previous studies have shown that GaN-based devices are at risk of degradation or failure when exposed to radiation environments [22-30].

Consequently, the impact of proton irradiation on GaN-based power devices represents a critical reliability concern. Numerous proton irradiation experiments have been performed on GaN-based power devices [31-36]. Yue et al. [35] conducted 3 MeV proton irradiation experiments on AlGaN/GaN HEMTs with a total fluence reaching 5×10^{14} p/cm^2. The results showed that the saturation current of the device was reduced by 14.6%, the threshold voltage (Vth) shifted forward by 0.35 V, and the inverse gate current was significantly reduced. The main degradation mechanism is thought to be an increase in the density of negatively charged traps in the channel. Kim et al. [36] carried out proton irradiation experiments at 0.5 MeV, 5 MeV, and 60 MeV on AlGaN/GaN HEMTs. The results showed that the transfer properties decayed most after 0.5 MeV irradiation because low proton energy produces larger non-ionizing energy loss. The gate leakage current of the fabricated HEMTs decreased with increasing irradiation energy due to the formation of an interfacial oxide layer caused by proton radiation between the gate and AlGaN layer. While these studies elucidate electrical performance degradation mechanisms, they fail to address the ultimate impact on device lifespan—a paramount consideration for aerospace applications where long-term reliability determines mission success. Therefore, further research is needed to achieve the long-term stable space application of GaN power devices.

Building upon the identified limitations in prior research, this study systematically investigates the energy-dependent effects of proton irradiation on the long-term reliability of gate oxides in Cascode GaN power devices. Using the time-dependent dielectric breakdown (TDDB) method, we found that the time tolerance for gate oxide breakdown of the device after low-energy proton irradiation is the shortest. Leakage paths are formed by proton irradiation-induced defects in the gate oxide layer, resulting in increased leakage current risks. Furthermore, the SRIM simulation method was employed to elucidate the basic mechanism of the enhanced damage effect due to low-energy proton irradiation.

Sample and Methods

Sample

The samples selected for this experiment are Common-gate and Common-source (Cascode) structure enhanced GaN power devices from Transphorm. The device consists of a high-voltage depletion-mode GaN HEMT and a low-voltage enhancement-mode Si MOSFET, and the device structure is shown in Fig. 1 Figure 1: see original paper. Since the drain-source voltage of the Si MOSFET provides a negative bias voltage to the gate-source voltage of the GaN HEMT, the switching state of the GaN HEMT can be controlled by controlling the switching state of the Si MOSFET, thus achieving normally-off characteristics. Fig. 1(b) shows the device package diagram. We used FIB and SEM methods to analyze the layered structure of Cascode GaN power devices, and the results are shown in Fig. 1(c). The rated operating voltage for GaN power devices is 650 V, and the threshold voltage is 3.3 V to 4.8 V.

Irradiation Experiments

The proton experiment was carried out at the Xi'an 200 MeV Proton Accelerator Facility (XiPAF). Protons with energies of 25 MeV, 60 MeV, and 100 MeV were used for experiments. The total fluence during the experiment was set to 2×10^{11} and 5×10^{11} p/cm^2, and the fluence rate was about 2×10^9 p/cm$^2 \cdot$ s. The irradiation time was about 100 s to 250 s. Bias voltages of 550 V, 600 V, and 650 V were applied to the samples, respectively. The experimental temperature was room temperature. Two to three samples were irradiated under each experimental condition to eliminate randomness.

Time-Dependent Dielectric Breakdown Methods (TDDB)

Since the 1990s, TDDB testing has served as a standard methodology for gate oxide reliability assessment in power MOSFETs [37]. According to the method of applying the electric field to the device, TDDB lifetime prediction can be divided into constant voltage (current) and ramp voltage (current). This study employs the constant voltage method, which can obtain the time-to-failure of the device, evaluate the quality of the gate oxide through Weibull distribution statistics, and further estimate the lifespan of the gate oxide layer. The constant voltage TDDB test is conducted at a voltage slightly lower than the gate breakdown voltage to determine the breakdown time and analyze the results. The slightly lower voltage itself is not sufficient to cause intrinsic breakdown. However, because of defects in the oxide layer during the application of electrical stress, charges accumulate near the defects or are captured by the defects after a certain period, leading to breakdown. Time-dependent gate oxide breakdown is a major factor affecting device reliability. Generally speaking, breakdown occurs due to a high electric field and excessive current in the oxide layer, leading to charge accumulation.

Stopping and Range of Ions in Matter Simulation Method (SRIM)

SRIM employs the Monte Carlo method to track the motion of a large number of incident particles through computer simulation [38]. It can calculate various physical processes of particle beams in different materials, including scattering, escape, energy deposition, transport, and the analysis of the radiation hardening characteristics of materials. The position of the particle, the energy loss, and various secondary particle parameters are stored throughout the tracking process. The collision parameters are randomly selected to simulate the collision process and calculate the process of incident ions colliding from the moment they enter the target until they lose energy and stop or exit the target. Finally, the expected values of various required physical quantities and the corresponding statistical errors are obtained. Since the results of the calculations have statistical significance, only when the number of ions calculated is sufficiently large can the required calculation accuracy be achieved. SRIM provides two different interfaces: as shown in Figure 2 Figure 2: see original paper, the SRAM program interface allows users to input the state of the target material and the incident particles and set the energy range of the incident particles. This interface is mainly used to calculate the penetration depth of particles with different energies in the target material. The other interface is the TRIM program interface, as shown in Figure 2(b). Through this interface, users can calculate parameters related to the energy loss of particle beams in target materials, the number of vacancies produced, and the slowing of radiation damage to materials. In this article, the functionality of TRIM is mainly used.

Results and Discussion

I-V Characteristic Results

The I-V characteristic curves of Cascode structure enhanced GaN power devices before and after proton irradiation are shown in Fig. 3 [Figure 3: see original paper]. The device threshold voltage changes after proton irradiation with energies of 25 MeV, 60 MeV, and 100 MeV are given in Fig. 3(a). As can be seen in the figure, the threshold voltage of the devices exhibited negative drift after proton irradiation. Data are statistically presented in Table 1 . The threshold voltage drift becomes more pronounced with an increase in proton fluence and bias voltage, which is consistent with previous experimental results [39-41]. The gate characteristics of the devices are represented by Fig. 3(b), from which it can be seen that the gate damage of the devices with 25 MeV and 60 MeV proton irradiation is more severe. After 25 MeV irradiation, the gate leakage current increases from 4.18×10^{-12} A to 4.42×10^{-10} A. After 60 MeV irradiation, the gate leakage current increased from 3.88×10^{-12} A to 3.81×10^{-10} A. The gate leakage current increases by two orders of magnitude. The gate characteristics of the devices are almost unchanged after 100 MeV proton irradiation. Fig. 3(c) shows the output characteristic curves of the device, which shows a slight increase in the drain leakage current after proton irradiation.

Comparative analysis of pre-irradiation and post-irradiation electrical characteristics reveals that the observed device degradation originates primarily from gate-related damage mechanisms. This manifests itself as a negative drift of threshold voltage and an increase in gate leakage current. The threshold voltage negative drift indicates that the switching capability of the gate is degraded. The gate characteristics of the Cascode GaN power device are mainly controlled by the Si MOSFETs, as can be seen from the presentation in Fig. 1(a). For gate oxide transistors, the threshold voltage drift is due to a combination of oxide trap charge and interface trap charge [42]:

$$\Delta V_{th} = \Delta V_{ot} + \Delta V_{it}, \quad \Delta V_{ot,it} = \frac{1}{C_{ox} t_{ox}} \int_0^{t_{ox}} \rho_{ot,it}(x) x \, dx$$

where ΔV_{ot} is the oxide trap charge, ΔV_{it} is the interface trap charge, C_{OX} is the capacitance per unit area of the gate oxide layer, t_{ox} is the oxide layer thickness, and $\rho_{ot,it}(x)$ is the charge distribution of the radiation-induced oxide trap charge or interface trap charge. At high dose rates and short periods of time, the neutralization of the oxide trap charge is small, resulting in a high oxide trap charge density. In contrast, interfacial trap charges do not have enough time to accumulate and usually have small densities [44]. In other words, the oxide trap charge generated by proton irradiation plays a major role in the threshold voltage drift. The increase of gate leakage current indicates the deterioration of insulation characteristics of the gate. The degradation of the insulating properties of the gate oxide is usually caused by defects or conductive channels generated by localized hot carrier stresses in the drain [43]. From the above analysis, it can be concluded that the defects generated in the oxide layer are the main reason for the degradation of the device gate characteristics due to proton irradiation.

TDDB Test Results and Discussion

To investigate the impact of proton irradiation-induced defects on the long-term reliability of Cascode GaN power devices, we conducted a comparative TDDB analysis of gate oxide layers pre-irradiation and post-irradiation. The TDDB experiment adopts the constant voltage stress (CVS) method. First, the time-zero dielectric breakdown (TZDB) method is used to determine the accelerated stress test range. It is specified that breakdown occurs when the gate current reaches 0.1 A. As shown in Fig. 4(a) [Figure 4: see original paper], when the gate voltage reaches about 47 V, the device will be broken down instantly. In order to complete the experiment more accurately and quickly, a bias voltage of $V_{GS} = 45$ V is selected in the TDDB test. Fig. 4(b) shows the curve of the gate leakage current of the devices before and after proton irradiation as a function of time under constant stress at the gate. As can be seen from the figure, the device gate leakage current continues to decrease before breakdown. This is the gate breakdown characteristic of silicon-based devices, which further indicates that the gate damage caused by proton irradiation is dominated by the damage of cascading Si-based transistors. The decrease in current indicates that the net negative charge in the device is captured [44]. The breakdown time of the unirradiated devices is about 28225 s. After 100 MeV proton irradiation of the device, the breakdown time is almost constant, about 27985 s. The breakdown time of the device after 60 MeV proton irradiation is about 26892 s, which is shortened by about 4.72%. The breakdown time of the device after 25 MeV proton irradiation is about 22535 s, which is shortened by about 20.16%.

The TDDB failure models widely used at present include the E model and 1/E model [45, 46]. The E model, also known as the thermochemical model, is suitable for devices with thicker gate oxide layers. The 1/E model is more suitable for devices with gate oxide layer thickness <5 nm. As shown in Fig. 1(c), the thickness of the gate oxide layer of the experimental sample is about 149 nm, so the E model should be used for failure analysis. The basic idea of the E model is that as the defects in the oxide layer increase, when the defects in the oxide layer are connected into a leakage path, the oxide layer undergoes dielectric breakdown. Fig. 5 [Figure 5: see original paper] shows a schematic diagram of the leakage paths in the oxide layer before and after proton irradiation. When a high voltage is applied between the upper and lower interfaces of the oxide layer, the defects in the oxide layer will form electron traps, randomly distributed within the oxide layer. Each electron trap has the ability to capture electrons under the influence of the electric field in the oxide layer. After proton irradiation, the number of defects in the oxide layer increases, and the regions where electron traps capture electrons may overlap, forming a current path from the upper interface of the oxide layer to the lower interface, as shown in Fig. 5(b). Therefore, proton irradiation leads to a reduction in the gate-oxide layer time-to-breakdown of the device.

It is also common to utilize the gate oxide layer cumulative charge to assess the magnitude of the device breakdown time, and thus the gate oxide layer lifetime. The cumulative charge is shown by eq. (3) [43]:

$$Q_{BD} = \int_0^{t_{BD}} J\,dt$$

where t_{BD} is the gate-oxide breakdown time and J is the gate leakage current. According to the calculation, Q_{BD} is 0.197 C before proton irradiation, Q_{BD} is 0.212 C after 100 MeV proton irradiation, Q_{BD} is 0.275 C after 60 MeV proton irradiation, and Q_{BD} is 0.299 C after 25 MeV proton irradiation, which increases by 40% compared with before irradiation. The accumulated charge of the gate oxide layer increases after irradiation and the lifetime of the gate oxide layer decreases. This charge-to-breakdown value has been used for several years as the most important reliability figure-of-merit for oxides. The TDDB method enables precise reliability evaluation of gate oxide layers, allowing quantitative determination of the failure threshold for GaN power device gate dielectrics in space radiation environments.

SRIM Simulation Results and Discussion

Through the analysis of proton irradiation experiments and TDDB experimental results, it is found that the influence of 100 MeV proton irradiation on the device is smaller than 25 MeV and 60 MeV, and the phenomenon of low-energy damage is more serious. This is due to the fact that protons travel essentially in a straight line through the material. The higher the proton energy, the smaller the interaction cross-section between the proton and the target nucleus, and the smaller the average energy transferred to the target nucleus [47, 48]. With the increase of proton energy, the radiation damage region gradually moves deeper into the device, away from the sensitive gate oxide layer region. We simulated the interaction cross-sections between protons at different energies and the target using SRIM software, as shown in Fig. 6 [Figure 6: see original paper]. The simulation results confirm the above statement that the irradiation damage region gradually moves away from the gate oxide layer as the proton energy increases (marked by the red arrow). The interaction radii of protons at 25 MeV, 60 MeV, and 100 MeV are 6×10^{-8}, 2.8×10^{-8}, and 2×10^{-8} Ang/Ion, respectively. In comparison, the cross-sectional radius produced by 25 MeV proton irradiation (circled in red dashed lines) is the largest. We also simulated the number of vacancies generated by protons of different energies in Si MOSFET transistors, as shown in Fig. 6(d). Among them, the 25 MeV protons produce the most vacancy defects in the device' s sensitive layer. These two factors eventually lead to enhanced damage from low-energy proton irradiation. The simulation results are consistent with the experimental analysis results and have mutually verified each other. In future work, we plan to incorporate nanoanalytical techniques from chemical engineering to further extend the scope of this research [48–52].

Conclusion

The impact of proton irradiation with different energies on the long-term reliability of the gate oxide for Cascode GaN power devices has been investigated in this paper. The TDDB experimental method and SRIM simulation method show that proton irradiation introduces a large number of defects in Cascode GaN power devices, and low-energy protons make the device more sensitive. Through the analysis of experimental results and the equation of the electrical characteristics of the device, it can be seen that the oxidation trap charge introduced by proton irradiation in the oxide layer is the main factor leading to the deterioration of the gate performance of the device. The degradation of gate performance indicates that gate switching capability and gate insulation characteristics are damaged, which is detrimental to the long-term reliable application of the device. To this end, we used the TDDB experimental method to test the gate tolerance of the device before and after proton irradiation. A constant gate bias voltage $V_{GS} = 45$ V is applied to both the unirradiated and irradiated devices. The experimental results show that the gate dielectric breakdown time of the irradiated device becomes shorter and the lifetime of the gate oxide layer of the device decreases. This is because proton irradiation introduces defects in the device' s oxide layer, which form electron traps that capture electrons under the influence of an electric field. The accumulation of a large number of electron traps will form one or more channels from the upper interface of the oxide layer to the lower interface, which serve as leakage paths. When enough electrons are captured by the traps, the device gate will undergo breakdown. Furthermore, it has been found that 25 MeV and 60 MeV protons cause more damage to the device than 100 MeV protons. This phenomenon is well explained by simulating the interaction between protons and devices of different energies using the SRIM method. The simulation results indicate that 25 MeV proton irradiation introduces more vacancy defects into the device. The radiation damage region of the low-energy protons is closer to the device' s sensitive area and has a larger effective range. This work systematically revealed the microscopic mechanism of degradation of the electrical properties of Cascode GaN power devices caused by proton irradiation. The results of this paper can provide theoretical support for further improving the long-term reliability of gate oxides in Cascode GaN power devices.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Ru-Xue Bai, Hong-Xia Guo, Yang-Fang Li, Wu-Ying Ma, and Ji-Fang Li. The first draft of the manuscript was written by Ru-Xue Bai, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The data that support the findings of this study are openly available in Science Data Bank.

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