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EXPERIMENTAL STUDY ON PROTON IRRADIATION EFFECT OF GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTOR

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Abstract

As a third-generation power semiconductor device, gallium nitride (GaN) high electron mobility transistor (HEMT) has a broad application prospects in the aerospace field. However, when a spacecraft is performing a flight mission, the GaN HEMT will inevitably be affected by the irradiation of high-energy charged particles from the space environment, most of which are protons. Therefore, it is of great significance to understand the effect of proton irradiation on GaN HEMT performance for its future development in the space field. In this paper, the proton radiation effect of GaN HEMT is studied by means of a medium energy proton irradiation platform. After proton irradiation, the threshold voltage of the GaN HEMT decreases, and the lower the incident proton energy, the more obvious the threshold decreases. The output characteristics curve, off-state leak current and gate forward leakage current of the GaN HEMT all increase after proton irradiation. After annealing at room temperature for 10 days, the electrical parameters of the GaN HEMT changed by proton irradiation are restored to the corresponding values before the proton irradiation. These changes indicate that medium energy proton irradiation with a fluence of 10^{12} p/cm^2 can improve the GaN HEMT performance, and the related reasons are discussed in detail.

INTRODUCTION

As an important third-generation semiconductor material, gallium nitride (GaN) has the advantages of high breakdown electric field, high electron saturation speed, high operating temperature and strong radiation resistance, and has broad application prospects in the aerospace field in the future [1, 2]. GaN HEMT is an important member of GaN-based electronic devices, and has super advantages in high frequency, high power, high temperature and high voltage applications. Therefore, GaN HEMT is widely considered to play an important role in spacecraft power supply and RF communication and other important fields in the future. However, GaN HEMT will inevitably be affected by the space radiation environment when the spacecraft performs relevant space flight missions [3–5]. Due to the wide band gap of GaN, GaN-based electronic devices should have an excellent radiation resistance in theory. Unfortunately, the radiation resistance of GaN HEMT is often affected by the preparation process and device structure, so the current radiation resistance of GaN HEMT still fails to reach the expected target.

Due to proton accounts for more than 85% and 90% of galactic cosmic rays and solar cosmic rays [6], respectively, the research work related to proton radiation effect of GaN HEMT has been widely concerned. White et al. found that GaN HEMT performance did not change significantly when proton fluence is lower than 10^{14} p/cm^2, the degradation of GaN HEMT is enhanced by the proton fluence when the proton fluence was greater than 10^{15} p/cm^2 [7]. Kim et al. found that when the proton fluence is 10^{15} p/cm^2, the degradation caused by low-energy proton is more serious than that caused by high-energy proton [8], the off-state stress creates more irradiated defects in GaN HEMT, while annealing can remove the stress-generated defects [9]. Greenlee et al. found that proton irradiation broadened the heterojunction interface in GaN HEMT, and then decreased the carrier density and mobility simultaneously [10]. Zheng et al. first observed changes in defects at the AlGaN/GaN heterojunction interface in GaN HEMTs after proton irradiation [11]. CareyIV et al. found that increasing the Al concentration can effectively weaken the effect of proton irradiation on GaN HEMT performance [12].

Previous researches on proton radiation effects of GaN HEMT are based on proton irradiation experiments with energy less than 10 MeV, and all the studies show that proton irradiation degrades the device performance. At present, the research work related to the radiation effect of medium-energy proton on GaN HEMT is rarely reported. Therefore, the proton radiation effect of GaN HEMT has been studied systematically through the medium energy proton irradiation platform in this paper. Different from previous research results, our research show that the electrical performance of the GaN HEMT is improved after medium-energy proton irradiation with fluence of 10^{12} p/cm^2. The deep physical mechanism of improving GaN HEMT performance by medium-energy proton irradiation is discussed in detail in this work.

EXPERIMENTAL DETAILS

In this experiment, eight qualified enhanced GaN HEMTs from the same batch produced by China Xinguan Semiconductor Co., LTD were randomly selected, and the official model of the GaN HEMTs is XG65T125PS1B. The proton irradiation experiment of the GaN HEMT was carried out in the medium-energy proton irradiation platform of China institute of atomic energy (CIAE), as shown in Fig. 1. The proton beam induced by the 100 MeV high-current proton cyclotron (CYCIAE-100) passes through different energy drop plates, and the proton energy decreases to 30 MeV, 40 MeV, 60 MeV and 90 MeV, respectively. During irradi-

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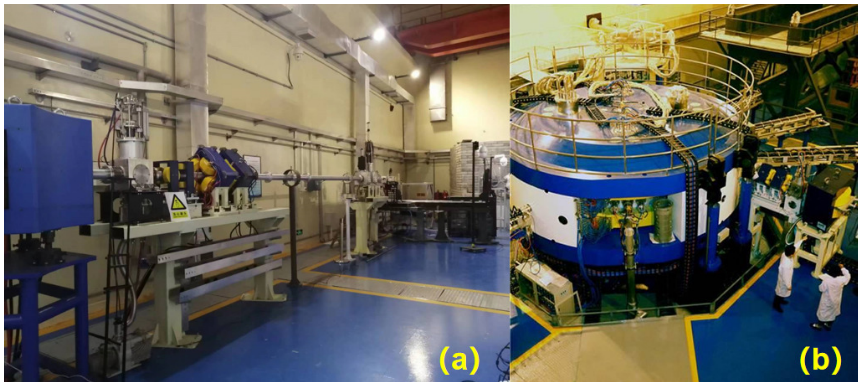

Figure 1: Schematic of the medium-energy proton irradiation platform (a) of the CYCIAE-100 high current proton cyclotron(b).

ation, the proton fluence rate was set to 10^8 p/cm^2 s, and the total fluence to the GaN HEMT was 10^{12} p/cm^2, all electrodes of the GaN HEMT were suspended. In order to ensure the accuracy of the experimental data, two devices A and B are used for the irradiation experiment of the same energy proton. The electrical parameters of GaN HEMT were measured at room temperature immediately after proton irradiation using the test system shown in Fig. 2. After annealing at room temperature for 10 days, the electrical parameters of the GaN HEMT were measured again by this system.

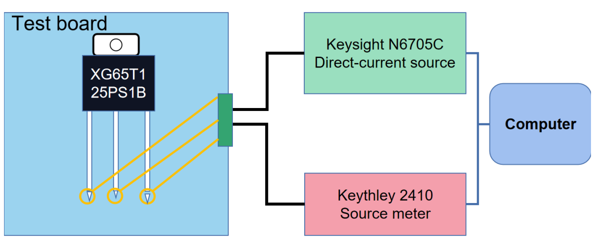

Figure 2: Electrical parameter test system of the GaN HEMT before and after proton irradiation.

RESULTS AND DISCUSSION

Gate-source threshold voltage is the turning on voltage of the enhanced GaN HEMT, the typical gate-source threshold voltage of the GaN HEMT according to the manual is 1.84 V. Figure 3 shows the change of gate-source threshold voltage of GaN HEMTs after proton irradiation with different energy, and the dash line in the figure represents the typical gate-source threshold voltage of the GaN HEMTs. In general, the threshold voltage of GaN HEMT decreases after proton irradiation. The higher the proton energy, the less the GaN HEMTs gate-source threshold voltage decreases. The experiments of Abbate et al. also showed that the gate-source threshold voltage of GaN HEMT decreased by 1 V after being irradiated with 3 MeV proton at an fluence of 4×10^{14} p/cm^2 [13]. The results of Kim et al. showed that the degradation of GaN HEMT electrical properties caused by low-energy proton irradiation was more serious than that caused by high-energy proton irradiation [9]. The results show that the electrical properties of GaN HEMTs used in this paper show the same degradation trend as that of the GaN HEMTs produced by foreign manufacturers after proton irradiation. Therefore, the research results of this work are reliable. In this experiment, the reduction of the gate-source threshold voltage is relatively lower compared with other experiments due to the use of high energy and low fluence of protons for irradiation.

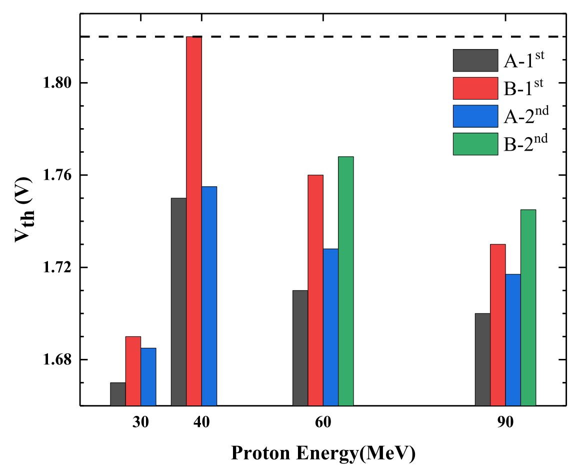

Figure 3: Gate-source threshold voltage of the GaN HEMT after proton irradiation with different energy.

At the same time, it is noted that the change trend of the gate-source threshold voltage caused by proton irradiation of 40 MeV is different from the results obtained after proton irradiation of other energies, this is because the 40 MeV proton irradiation experiment is carried out with other user experiments to save time. During the 40 MeV proton irradiation experiment, the GaN HEMTs are placed near the edge of the proton beam spot, and the total fluence of proton irradiation to the GaN HEMTs may be less than 10^{12} p/cm^2. Therefore, the gate-source threshold voltage reduction of the GaN HEMTs caused by proton irradiation with 40 MeV is lower than that caused by proton irradiation with other energy.

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The gate-source threshold voltage of the GaN HEMT can be expressed by the following formula:

$$V_{th}(x) = \phi(x) - \Delta E_C(x) - \frac{qN_d d_d^2}{2\varepsilon(x)} - \frac{\sigma(x)}{\varepsilon(x)} \quad (1)$$

where, $\phi(x)$ is the height of the Schottky barrier, $\Delta E_C(x)$ is the conduction band discontinuity, $\sigma(x)$ is the polarization charge concentration, N_d, d and $\varepsilon(x)$ are the doping concentration, thickness and dielectric constant of AlGaN layer, respectively. Among these parameters, $\phi(x)$, N_d and $\sigma(x)$ are the main parameters affected by proton irradiation. The hole generated by ionization is captured by the vacancy defect generated by proton irradiation and becomes a fixed positive charge, and the electric field generated by it will enhance the discontinuity of the conduction band, increase the 2DEG carriers, and then make the gate-source threshold voltage drift negatively.

The output characteristic of the GaN HEMT is defined as a function of the current between the drain and source poles and their voltages when different voltages are applied to the gate. Figure 4 shows the output characteristic curve of GaN HEMTs before and after proton irradiation. Since the output characteristic curves of the GaN HEMTs in groups A and B are consistent, only the output characteristic curve of the GaN HEMTs in group A is shown here. As can be seen from the figure, the output characteristic curve of the GaN HEMTs increased after proton irradiation compared with that before irradiation, indicating that the saturation current of the GaN HEMTs increased. The larger the V_{GS}, the more obvious the increase of the GaN HEMT output characteristic curve after proton irradiation. The GaN HEMTs output characteristic curve recovered to the corresponding value before proton irradiation after 10 days annealing at room temperature, and the GaN HEMTs output curve after 40 MeV proton irradiation is the most close to the corresponding value before proton irradiation, because the proton fluence in 40 MeV proton experiment may be lower than 10^{12} p/cm^2.

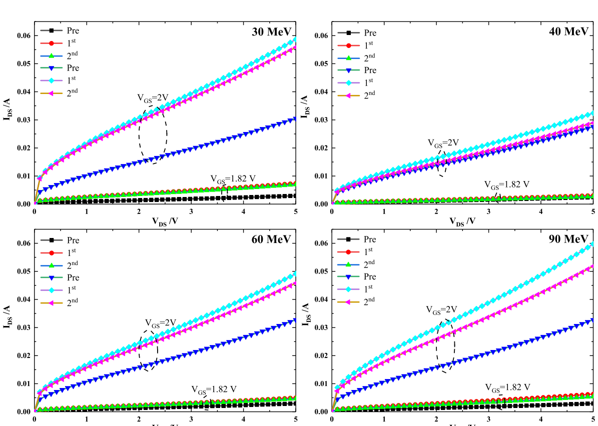

Figure 4: Output characteristic curves of the GaN HEMT before and after proton irradiation with different energy.

For GaN HEMT, the current expression at position x of the 2DEG channel is as follows:

$$I = qn_s(x)Wv(x) \quad (2)$$

$$v(x) = \begin{cases} \mu E, & E < E_C \\ v_s, & E \geq E_C \end{cases} \quad (3)$$

$$n_s = \frac{\varepsilon(n)}{qd}\left[V_{gs} - V_{th} - \frac{E_F}{q}\right] \quad (4)$$

where, $n_s(x)$ is the carrier concentration in 2DEG, W is the gate width, $v(x)$ is the carrier migration velocity at channel position x, μ is the carrier mobility, V_s is the saturation velocity of the carrier, d is the distance between the gates, V_{th} the the gate-source threshold voltage, ε is the dielectric constant of AlGaN, E_F is the Fermi level of the two-dimensional well, and n is the mole fraction of Al in AlGaN. Related studies have shown that displacement defects caused by proton irradiation will change the mobility of carriers. According to the above formula, the increase of carrier mobility will increase the output characteristics of the GaN HEMT. Due to irradiation defects, proton irradiation will reduce the gate-source threshold voltage of the GaN HEMT, increase the carrier concentration, and then increase the output characteristic.

Figure 5 shows the off-state leakage current of the GaN HEMTs before and after proton irradiation. It can be seen from the figure that after proton irradiation, the off-state leakage current of the GaN HEMTs has a significant increase compared with that before proton irradiation, especially when the V_{DS} is ≤250 V. The carriers concentration at the AlGaN/GaN interface in the GaN HEMTs after proton irradiation depends on the competition between carrier removal due to Ga vacancies and carrier increase due to the total ionizing dose effect. When the irradiated proton energy is low and the fluence is high, the displacement damage of the GaN HEMTs is dominant, and the carrier concentration in 2DEG decreases, which makes the off-state leakage current of the GaN HEMT decrease. When the proton energy is high and the fluence is low, the total ionizing dose effect is more significant, resulting in the increase of the off-state leakage current. The 40 MeV proton irradiation experiment shows that the off-state leakage current of the GaN HEMT decreases after proton irradiation, indicating that the proton fluence is less than 10^{12} p/cm^2 at this time.

Figure 6 shows the change of static forward gate current of the GaN HEMT when the gate voltage is equal to 20 V after proton irradiation with different energy, where the positive value represents the increase of static forward gate current and the negative value represents the decrease of static forward gate leakage current. The first test shows that proton irradiation increases the static forward gate current of the GaN HEMT, which is consistent with the change trend of the off-state leakage current. After annealing at room temperature for 10 days, the second test found that the static forward gate current of the GaN HEMT decreased and is smaller than that before proton irradiation. Wang et al. also observed similar changes in neutron irradiation experiments

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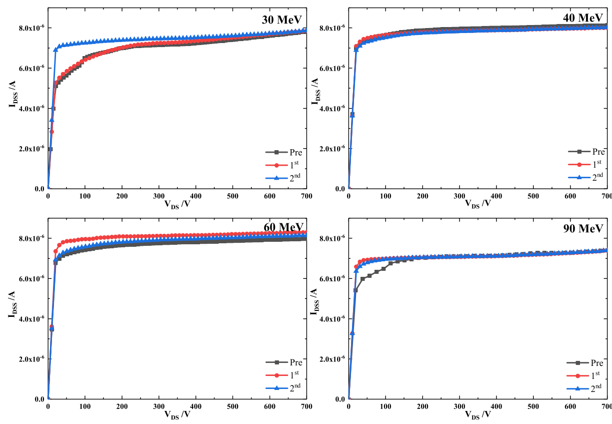

Figure 5: The off state leakage current of the GaN HEMT before and after proton irradiation.

on GaN HEMT [14], the static forward gate current of the GaN HEMT increased after neutron irradiation, and the static forward gate current of the GaN HEMT recovered to the same value as that before irradiation after 24 hours annealing at room temperature.

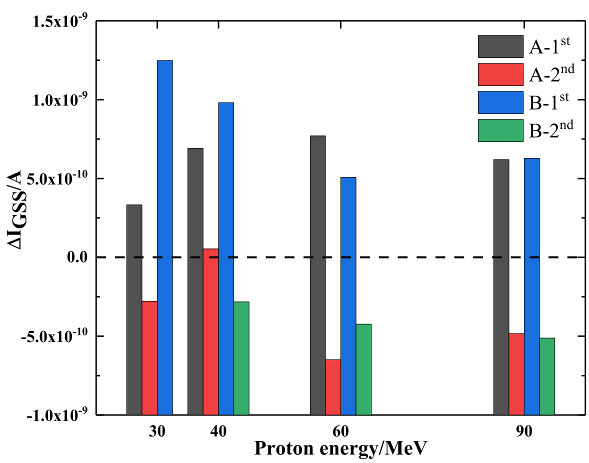

Figure 6: Static forward gate current of the GaN HEMT after proton irradiation with different energy.

The density of interface states at the Schottky junction in the gate decreased by proton irradiation, and the energy level of the Schottky contact interface defect expanded to the shallow energy level. Previous studies have found that the interface states density of AlGaN/GaN channel region increases slightly. The decrease of interface state density will lead to the decrease of the number of channels through which the auxiliary electron tunneling through the barrier, which will reduce the static forward gate leakage and improve the static forward gate leakage characteristics of the GaN HEMT. At the same time, proton irradiation will continuously shallower the interface energy level, which will theoretically lead to the increase of static forward gate leakage.

CONCLUSION

In this work, the proton radiation effect of GaN HEMT was studied in detail by medium-energy proton irradiation experiment. The experimental results show that the gate-source threshold voltage of the GaN HEMT decreases after proton irradiation, and the output characteristics, off-state leakage current and static forward gate current increase. After annealing at room temperature for 10 days, these electrical parameters of the GaN HEMTbecome close to their pre-irradiation values. On the whole, the electrical properties of the GaN HEMT are improved by proton irradiation under the experimental conditions in this paper. The reasons for the improvement of the electrical properties of the GaN HEMT by medium-energy proton irradiation were preliminarily discussed in this paper, but the involved physical mechanism needs to be further studied.

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