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Study of proton irradiation effects on AlGaN/GaN high electron mobility transistors

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ABSTRACT

AlGaN/GaN high electron mobility transistors (HEMTs) were exposed to 3 MeV protons at fluences of 6×10^{13}, 4×10^{14} and 1×10^{15} protons/cm^2. The drain saturation currents decreased by 20% and the maximum transconductance decreased by 5% at the highest fluence. As the fluence increased, the threshold voltage shifted more positive values. After proton irradiation, the gate leakage current increased. The Schottky barrier height changed from 0.63 eV to 0.46 eV, and the ideality factor from 2.55 to 3.98 at the highest fluence. The degradations of electrical characteristics of AlGaN/GaN HEMTs are caused by displacement damages induced by proton irradiation. The density of vacancies at different proton fluence can be calculated from SRIM. Being an acceptor-like defect, the Ga vacancy acts as a compensation center. While N vacancy acts as a donor. Adding the vacancies model into Slivaco device simulator, simulation results match well with the trends of experimental data. Hall measurement results also indicate the concentration and mobility of 2DEG decrease after proton irradiation. It is concluded that the Ga vacancies introduced maybe the primary reason for the degradation of AlGaN/GaN HEMTs performance.

1. Introduction

III-Nitride semiconductors are characterized by wide band gap, high electron velocities and high thermal and chemical stability. They are promising materials for electronics and optical applications. Rapid developments of the space communication have generated much need for high efficiency devices that can operate at high frequency and handle high power in space. Compared to Si and GaAs-based devices, GaN-based devices are more radiation tolerant because of higher displacement threshold energy, which is inversely proportional to the lattice constant [1]. Therefore, many researches concentrate efforts on finding the radiation effects on GaN-based electronic devices such as high electron mobility transistors (HEMTs) [2–14]. To discover the device behavior in space environment, it becomes important to understand the degradation mechanisms of devices after exposure to radiation.

Devices employed in the space are exposed to both particle and electromagnetic radiation, such as electron, proton, photons, neutron, gamma ray, and alpha particles. Radiation effects include the effects of displacement damage and ionizing radiation. Earlier research shows that the ionization effects do not make significant contributions to radiation-induced damage in GaN-base devices [15,16]. So the main task of this work is to understand and characterize the displacement damage caused by proton radiation. Atoms will be displaced in crystal lattice and defect centers will be created by the incident protons. Defect centers degrade the carrier concentration in the two-dimensional electron gas (2DEG) through charge compensation and carrier removal, and degrade the carrier mobility through Coulomb interactions. Many previous researches concentrated on experiment results, but lacked the theoretical explain. In this work, proton irradiation effects are fully analyzed in theory.

2. Experimental details

The devices studied in this work were fabricated at Xidian University in China. The heterostructures were deposited on a silicon carbon substrate using metalorganic chemical vapor deposition (MOCVD). The AlGaN/GaN HEMT devices are mainly composed of 2-μm layer of GaN and 20-nm layer of AlGaN. The Al fraction in AlGaN layer is 0.3. The device processes include isolation with induced coupled plasma (ICP) etching, Schottky contacts with Ni/Au (20 nm/200 nm), Ohmic contacts with Ti/Al/Ni/Au (20 nm/120 nm/55 nm/45 nm), and so on. The gate length is 0.6 μm, and the gate width is 100 μm. A schematic cross section of this structure is shown in Fig. 1.

The AlGaN/GaN HEMTs were irradiated at the Peking University proton accelerator with 3 MeV protons. The proton fluences are 6×10^{13}, 4×10^{14} and 1×10^{15} protons/cm^2. The electrical characteristics of these devices were measured immediately after irradiation using an HP4156 semiconductor parameter analyzer.

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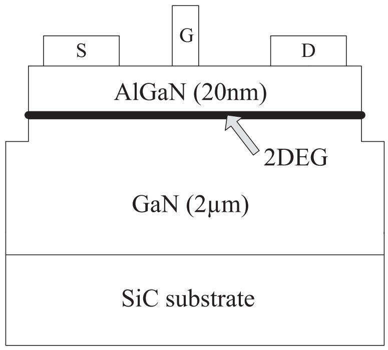

Fig. 1. A schematic cross section of AlGaN/GaN HEMT.

All the irradiations and measurements were carried on at room temperature.

3. Results and discussion

The output characteristics, the drain current (I_{ds}) vs. drain voltage (V_{ds}) of AlGaN/GaN HEMT before and after 3 MeV proton irradiation, are shown in Fig. 2. These results are similar to research results published previously [2,7,8]. No significant degradation of the electrical characteristics is observed after proton irradiation of 6×10^{13} protons/cm^2 fluence. When proton fluence rises to 1×10^{15} protons/cm^2, the curve shows obviously decrease. From the output curves, the drain saturation currents (I_{dsat}) are extracted. At V_{gs} = 1 V, I_{dsat} at different proton fluences are shown in Fig. 3. It is seen that I_{dsat} decreases by 5% at a fluence of 6×10^{13} protons/cm^2 and by 20% at a fluence of 1×10^{15} protons/cm^2.

Fig. 4 shows the transfer characteristics, the drain current (I_{ds}) vs. gate voltage (V_{gs}) of AlGaN/GaN HEMT before and after 3 MeV proton irradiation. These are measured at a drain voltage of 10 V. AlGaN/GaN HEMTs are depletion-mode, so the threshold voltage (V_{th}) is negative. As the fluence increases, the drain current decreases and V_{th} shifts toward more positive values. No significant degradation for V_{th} is observed after proton irradiation of 6×10^{13} protons/cm^2 fluence. The positive shifts in V_{th} of HEMTs are attributed to the Ga vacancies, which leads to an increase in density of acceptor-like traps. When proton fluence is low, the density of Ga vacancies introduced is negligible. When proton fluence goes up to 1×10^{15} protons/cm^2, V_{th} shows obviously positive shift. The density of Ga vacancies is high enough to lead to the degradation.

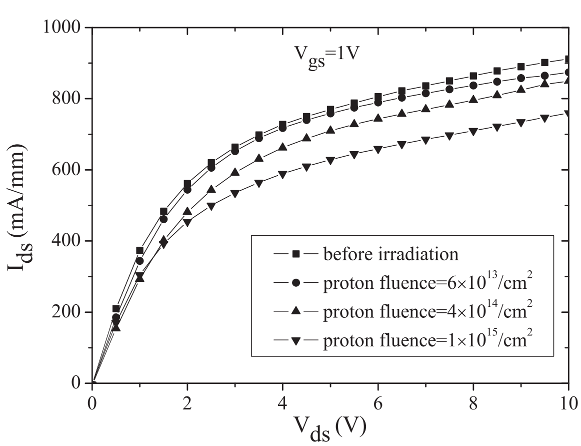

Fig. 2. Output characteristics of AlGaN/GaN HEMT at different proton fluences.

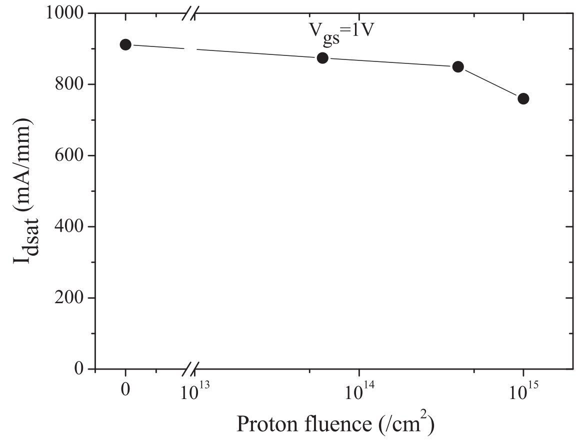

Fig. 3. Drain saturation currents I_{dsat} in AlGaN/GaN HEMT as a function of proton fluence.

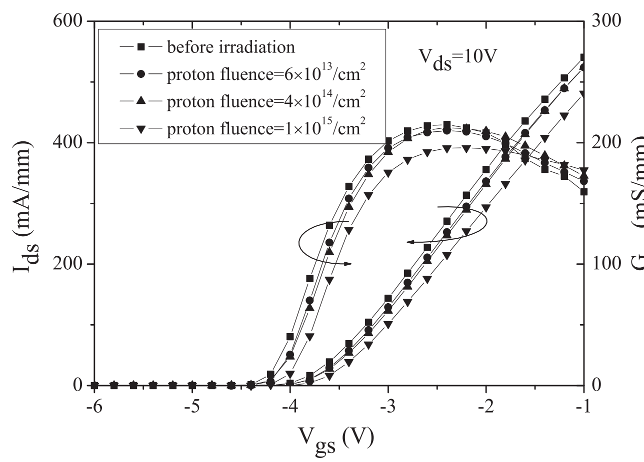

Fig. 4. Transfer characteristics of AlGaN/GaN HEMT at different proton fluences.

From the transfer curves, the maximum transconductances (G_{max}) are extracted. G_{max} at different proton fluences are shown in Fig. 5. It is seen that G_{max} decreases by 5% at a fluence of 1×10^{15} protons/cm^2. However, the degradation of G_{max} is not obvious, compared to the degradation of I_{dsat}. Device degradation occurs after high proton fluences.

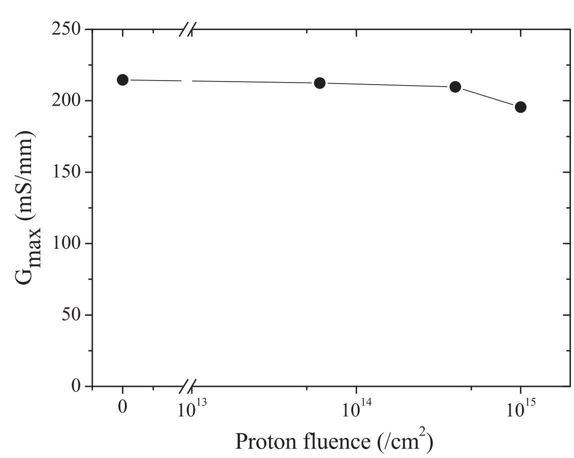

Fig. 5. The maximum transconductance G_{max} in AlGaN/GaN HEMT as a function of proton fluence.

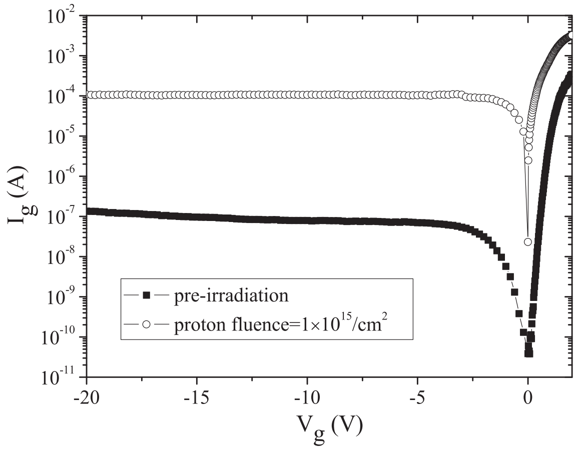

Fig. 6. Gate leakage I–V characteristics of AlGaN/GaN HEMTs before and after proton irradiation at fluence of 1×10^{15} protons/cm^2.

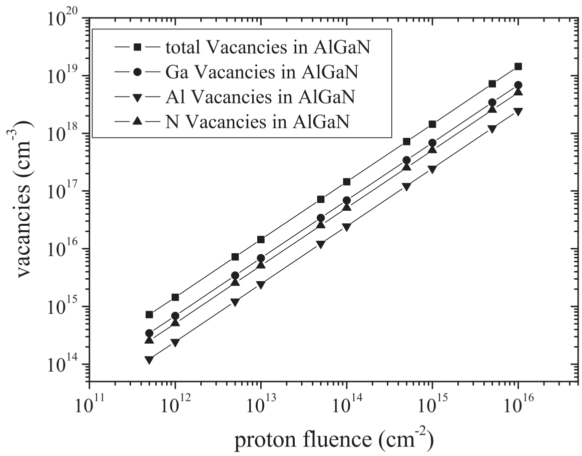

Fig. 7. Vacancies in the AlGaN layer as a function of proton fluence obtained from SRIM.

Table 1
The degradation of Schottky parameter after proton irradiation.

	Before irradiation	After irradiation (1×10^{15} protons/cm^2)
$\Phi_b(x)$	0.63 eV	0.46 eV
n	2.55	3.98

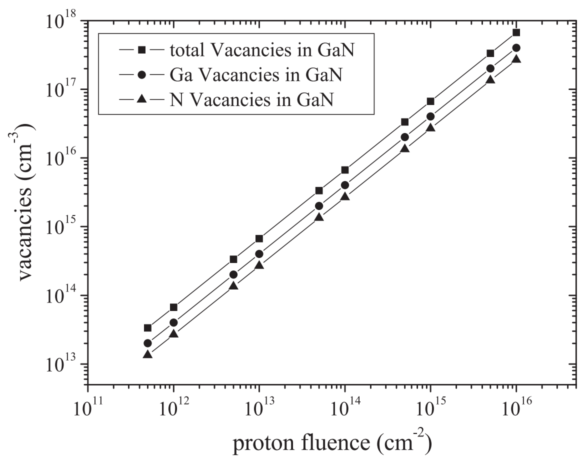

Fig. 8. Vacancies in 20-nm region of the GaN layer close to the AlGaN/GaN interface as a function of proton fluence obtained from SRIM.

Fig. 6 shows the forward bias and reverse bias gate I–V characteristics of AlGaN/GaN HEMTs before and after 3 MeV proton irradiation. It is observed that a fluence of 1×10^{15} protons/cm^2 of proton irradiation leads to the increase of the gate leakage current. The gate forms a Schottky contact with the structure. The Schottky barrier height can be calculated from the forward I–V characteristics. The barrier height is given by

$$\Phi_b(x) = \frac{kT}{q} \ln\left(\frac{AA^*T^2}{I_s}\right) \quad (1)$$

Here $A^* = \frac{4\pi qk^2m^*}{h^3}$ is Richardson's constant, A is area, I_s is saturation current, and T is the temperature. The slope of this plot is related to the ideality factor (n). Eq. (2) describes the ideality factor n.

$$n = \frac{lg\ e}{(kT/q)slope} \quad (2)$$

Table 1 shows the change of Schottky parameter caused by proton irradiation at fluence of 1×10^{15} protons/cm^2. It is seen that the Schottky barrier height decreases and the ideality factor increases significantly after proton irradiation. Defects induced by irradiation in the band gap and near the metal/AlGaN interface may act as tunneling sites, leading to increase gate current tunneling probability and decrease the Schottky barrier height [17].

The proton irradiation damage mechanism and range in GaN are simulated by SRIM. Energetic protons transfer a part of their kinetic energy to the Ga and N atoms through non-ionizing energy loss (NIEL). This energy displaces atoms from their lattice sites and creates charged defect centers. In the case of AlGaN/GaN HEMT, the main area is the interface between AlGaN and GaN. Hence, our study pays more attention to the AlGaN layer and 20-nm region of the GaN layer close to the AlGaN/GaN interface. According to the number of vacancies created in the given depth after energetic proton incidence, we can calculate the density of vacancies at different proton fluences. Fig. 7 shows the vacancies densities created in the AlGaN layer as a function of 3 MeV proton fluence. Fig. 8 shows the vacancies densities created in 20-nm region of the GaN layer close to the AlGaN/GaN interface as a function of 3 MeV proton fluence. The numbers are consistent with earlier research results [11,12].

From Figs. 7 and 8, it is seen that the density of Ga vacancies is significantly higher than that of N vacancies. The energy transferred to Ga atoms is higher than the energy transferred to N atoms, because the displacement energy of Ga atoms and N atoms are about 22 eV and 25 eV respectively [1]. As the fluence of the incident proton increases, the densities of Ga and N vacancies increase.

SRIM can simulate the number of vacancies in many regions of device, but cannot show us the electrical characteristics of these vacancies. For this study, it is very important to understand the effect of Ga and N vacancies on GaN devices. These vacancies reduce the majority carrier concentration, minority carrier lifetime and carrier mobility by the formation of traps. Trap centers, whose associated energy lies in a forbidden gap, exchange charge with the conduction and valence bands through the emission and capture of electrons. In this work, we consider that these vacancies are mainly responsible for the electrical characteristics degradation.

The Ga vacancy (V_{Ga}) has relatively low formation energy in n-type GaN when Fermi level is close to the conduction band. Being an acceptor-like defect, V_{Ga} acts as a compensation center. The Ga vacancies are mobile in wide range of temperatures typically used during growth or thermal annealing. It is likely that they migrate and from complexes with more stable defects.

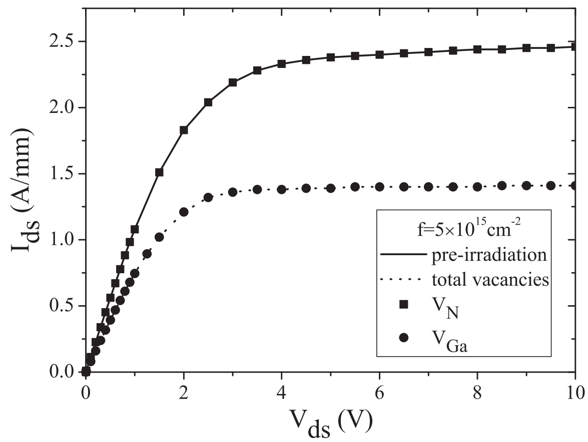

Fig. 9. Output characteristics of AlGaN/GaN HEMT at different vacancies model obtained from Silvaco device simulator.

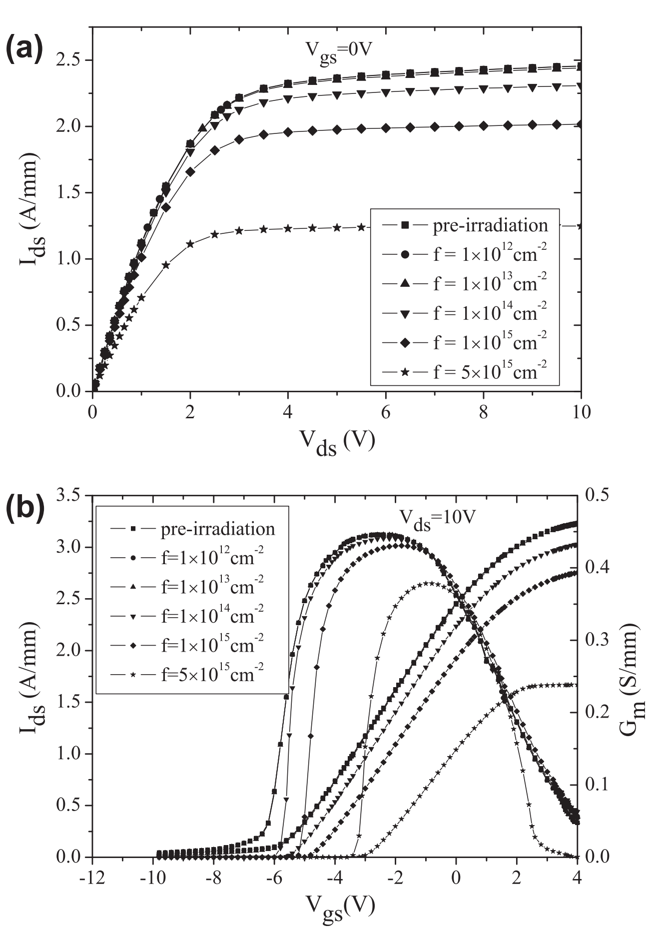

Fig. 10. Output (a) and transfer (b) characteristics of AlGaN/GaN HEMT at different proton fluences obtained from Silvaco device simulator.

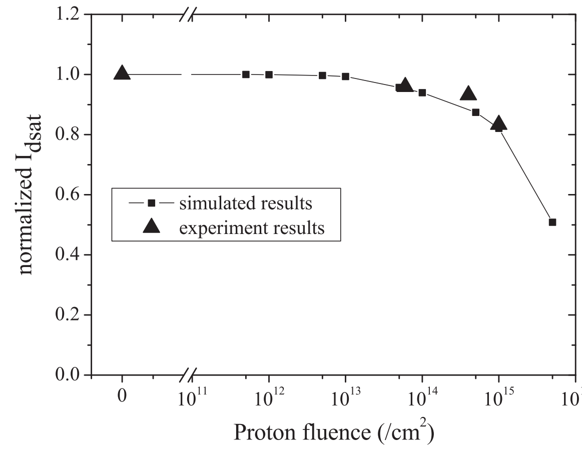

Fig. 11. Normalized I_{dsat} shift in AlGaN/GaN HEMT as a function of proton fluence.

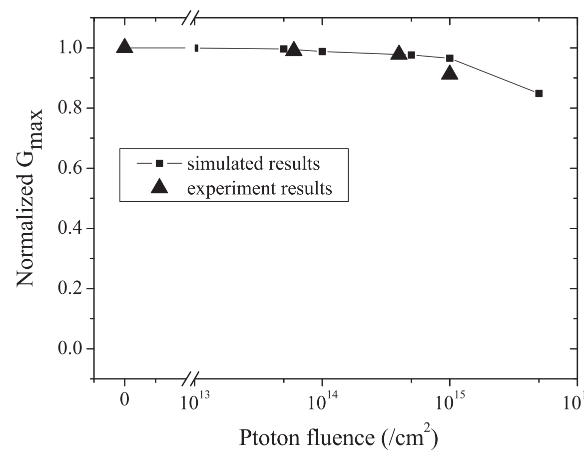

Fig. 12. Normalized G_{max} shift in AlGaN/GaN HEMT as a function of proton fluence.

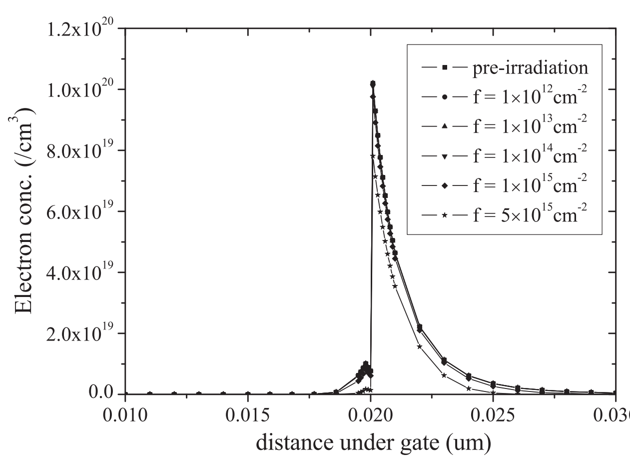

Fig. 13. The concentration distribution of 2DEG in AlGaN/GaN HEMT at different proton fluences.

First-principle calculations predict that several V_{Ga}-related defects may be responsible for YL in undoped-GaN. For Ga vacancies, the traps are formed the energy level of 0.86 eV from the valence band edge, the electron capture cross section is $\sigma_n = 2.7 \times 10^{-21}$ cm^2 and the hole capture cross section is $\sigma_p = 2.7 \times 10^{-14}$ cm^2 [18–23].

The first-principles calculations showed that N vacancy (V_N) might be formed in detectable concentrations in n-type GaN only under Ga-rich conditions. V_N acts as a donor. There is only one transition level for V_N in the gap which is 0.5 ± 0.2 eV above the valence band edge [22].

A divacancy (V_{Ga}–V_N) has relatively high formation energy in GaN and is unlikely to form in large concentrations. These vacancies are instable. They can form more stable complexes with other elements, such as H, O, and C. There are different transition levels

Table 2
The degradation of Hall parameters of AlGaN/GaN heterostructure after proton irradiation.

	Before irradiation	6×10^{13} protons/cm^2	4×10^{14} protons/cm^2	1×10^{15} protons/cm^2
2DEG concentration (/cm^2)	2.90×10^{12}	1.06×10^{12}	1.01×10^{12}	7.84×10^{11}
2DEG mobility (cm^2/V s)	1792.63	1422.28	1376.87	1083.78

in the gap for these complexes. It is possible that V_{Ga}, V_{Ga}–H, V_{Ga}–H_2, and V_{Ga}–H_3 exist simultaneously in GaN. They are deep acceptor-like traps. Regardless of these complexes and annealing effects, we only consider V_{Ga} and V_N introduced which can be calculated from SRIM directly.

The devices can be simulated using the Silvaco device simulator. Through introducing the model of Ga and N vacancies into Silvaco, we can directly understand the effects of vacancies on the performance of AlGaN/GaN HEMTs. The density of vacancies has been obtained from SRIM. We also know the energy level corresponding to Ga and N vacancies respectively. In simulation, we can accurately understand the effect of radiation-induced defects on the space charge and ultimately on the 2DEG by supposing that the polarization charge is not affected by proton irradiation, and $\sigma_{pol} = 1 \times 10^{13}$ cm^{-2}. Fig. 9 shows the output characteristics of AlGaN/GaN HEMT before and after proton irradiation at fluence of 1×10^{15} protons/cm^2 introducing Ga vacancies and N vacancies model into Silvaco simulator. It is observed that N vacancies as donors do not affect the electrical Characteristics of HEMTs. The degradation of I_{ds} is caused by Ga vacancies which act as acceptors.

Fig. 10 shows the simulated results by introducing Ga vacancies model into Silvaco. Fig. 10a and b are output and transfer characteristics of AlGaN/GaN HEMT at different 3 MeV proton fluences respectively. The electrical characteristics do not decrease obviously until the fluence up to 5×10^{15} protons/cm^2.

The drain saturation currents and the maximum transconductances are obtained. Fig. 11 shows the comparison of normalized I_{dsat} obtained from Silvaco simulation and the experimental data. Fig. 12 shows the normalized G_{max} obtained from simulation and experiments. The degradation trends of the experimental I_{dsat} and G_{max} match very well with the simulation results. Therefore, we think that the introduction of Ga vacancies into the proton-irradiation GaN and complexes related with Ga which act as acceptors maybe the primary reason for the degradation of device performances.

2DEG concentration as a function of proton fluences is extracted from Silvaco, shown in Fig. 13. As the proton fluence increases, the 2DEG concentration decreases. It is seen that the introduction of Ga vacancies influences the 2DEG density.

For better understanding the effects of proton irradiation on AlGaN/GaN HEMTs, the AlGaN/GaN heterostructures without done any device processes were measured before and after proton irradiation by Hall measurement. The results of 2DEG concentration and mobility at different fluences are shown in Table 2. As the proton fluence goes up, the 2DEG concentration and mobility decrease, which directly demonstrate that displacement damage induced by proton irradiation influences the electrical characteristics of AlGaN/GaN heterostructure.

4. Conclusions

After 3 MeV proton irradiation, the AlGaN/GaN HEMTs show significant degradation after proton radiation at fluence of 1×10^{15} protons/cm^2. As the fluence increases, the drain saturation current and maximum transconductance decreases, the threshold voltage becomes more positive and gate leakage current increases. The density of Ga and N vacancies caused by proton irradiation can be calculated by SRIM. Being a deep acceptor-like defect, Ga vacancy plays an important role in AlGaN/GaN HEMTs. Introducing the model of Ga vacancies to Silvaco, simulation results match well with the trends of experimental data. The results of Hall measurements also indicate that proton irradiation leads to the decrease of 2DEG concentration and mobility. All demonstrate the electrostatic effects of Ga vacancies are the primary cause for the degradation of AlGaN/GaN HEMTs electrical characteristics.

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