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Investigation of heavy ion irradiation effects on 650-V p-GaN normally-off HEMTs

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Abstract In this study, we investigate heavy ion irradiation effects on commercial 650 V p-GaN normally-off HEMTs. Ge and Cl ions are used to irradiate the GaN devices in the experiments. Ge and Cl ion beam irradiation have little impact on the output characteristics of GaN devices. After heavy ion irradiation, the leakage currents between source and drain electrodes increase significantly under off-state, decreasing the breakdown voltage (BV_{DS}) sharply. Additionally, Ge and Cl ion irradiation have little effect on the trap states under the gate electrode; thus, the gate leakage currents increase slightly. Many line-shaped crystal defects extending from the surface to the GaN buffer layer can be captured using a transmission electron microscope after Ge/Cl ion irradiation. The buffer layers of the irradiated devices were damaged, and the leakage path was generated in the buffer layer. Defect percolation process in buffer layer is the dominant factor of irradiated high-voltage GaN device failure.

Keywords heavy ions irradiation, p-GaN normally-off HEMTs, line-shaped crystal defects, leakage path, defect percolation process

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1 Introduction

Compared with the silicon (Si) bandgap of 1.12 eV, the gallium nitride (GaN) bandgap (3.4 eV) is much higher. The electric field strength and electron mobility in a compound semiconductor GaN are 10 and 2, respectively, higher than Si material. These excellent material properties translate into devices leading to higher breakdown voltage and lower on-resistance (R_{ON}), and GaN high electron mobility transistors (HEMTs) have shown tremendous potential for power electronics applications. Due to strong Ga- N bonds and higher displacement energy, GaN material possesses excellent chemical stability; thus, GaN-based HEMTs have great advantages in the space environment [1–4].

In previous studies, it has been found that the total-ionizing-dose irradiation effect has little influence on the failure of GaN devices [5–7]. However, the single event effect (SEE) has a significant effect on GaN devices [8, 9]. In the previously reported studies, the heavy ion irradiation experiments on GaN power electronic devices mainly focused on GaN HEMT devices under low voltage [10–12]. The results of heavy ion irradiation experiments under low voltage are qualified, but irradiated high-voltage GaN devices have failed [12]. Although possible failure mechanisms of SEEs in GaN devices were investigated through simulation [13, 14], the influence of heavy ion irradiation on high-voltage GaN HEMTs is still unclear and needs further investigation. The normally-off characteristics are required to guarantee a safe operation and simple gate drive configuration for power switching applications. Due to high electron mobility and being free from the problems of dielectric-layer defects and interface reliability, p-GaN normally-off

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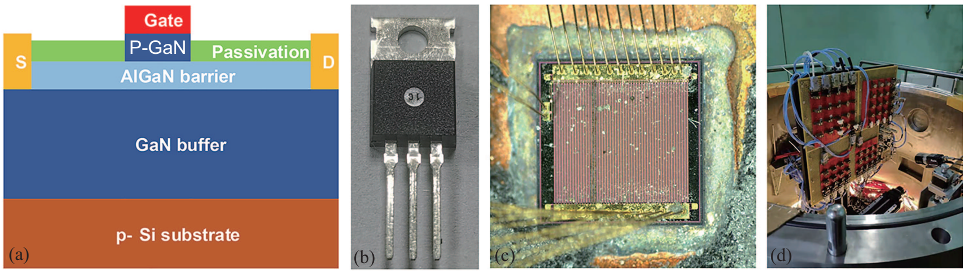

Figure 1 (Color online) (a) Cross-section of p-GaN HEMTs; the picture of the p-GaN E-mode HEMTs (b) before and (c) after removing the package shell; (d) the picture of tank used in this experiment.

Table 1 Specifications of GaN HEMTs used in this work

Item ($T = 25°$C)	Specified value
I_{Dmax}	20 A
R_{ON}	100 mΩ
V_{TH}	0.8–1.2 V
$\mathrm{BV_{DS}}$	650 V
$I_{\mathrm{D,leakage}}$	2–10 μA

HEMTs are the only commercially available normally-off GaN devices [15, 16]. Thus, it is necessary to perform heavy ion irradiation experiments based on p-GaN HEMTs.

In this study, the experiments of heavy ion (germanium (Ge) and chlorine (Cl)) irradiation on 650 V commercial normally-off p-GaN HEMTs were conducted, and the failure mechanism of devices under off-state high voltage was analyzed. After Ge and Cl ion irradiation, the leakage between the source and drain electrodes increased significantly, and the gate leakage current increased slightly. Ge and Cl ion irradiation had little effect on the trap states under the gate electrode. Additionally, many line-shaped crystal defects can be found in irradiated devices. The generated leakage path in the buffer layer is the dominant factor of irradiated GaN device failure.

2 Procedure and setup

The p-GaN E-mode HEMTs are manufactured by Xiamen Sanan Integrated Circuit Co., Ltd. (Figure 1(a)). The thicknesses of the AlGaN barrier, GaN channel, and GaN buffer layers are 20, 500, and 5000 nm, respectively. The devices tested in this study have a gate width (W_{G}) of 2000 μm × 50 μm, gate length (L_{G}) of 6 μm, gate-source distance (L_{GS}) of 6 μm, and gate-drain distances (L_{GD}) of 6 μm. The model of devices is SMG060E015L, and the parameters of the devices are presented in Table 1. At room temperature, the $\mathrm{BV_{DS}}$ of the device is 650 V, on-resistance (R_{ON}) is 100 mΩ, saturated output current (I_{Dmax}) is above 20 A, threshold voltage (V_{TH}) is 1.0 V, and leakage current ($I_{\mathrm{D,leakage}}$) under off-state is 2–10 A. Before conducting the heavy ion irradiation experiment, the package shells of the devices were removed using acid etching. Then, the electrical characteristics of each device were tested to eliminate the unqualified samples. Figures 1(b) and (c) show the picture of the p-GaN E-mode HEMTs before and after removing the package shell, respectively.

Heavy ion irradiation experiments were conducted using a tandem electrostatic accelerator at the China Institute of Atomic Energy. The heavy ions used in these experiments are Ge and Cl ions. The parameters of the two kinds of ions are shown in Table 2. The energies of Ge and Cl ions are 208 and 160 MeV, respectively. The values of linear energy transfer (LET) for Ge and Cl are 28.51 and 10.04 MeV·cm^2/mg, respectively, in GaN material. The ranges of Ge and Cl ions in GaN are 16.10 and 23.63 μm. The range value is related to the energy of ions and the density of the target material. The density of GaN is 6.1 g/cm^3, and the energies of Ge and Cl ions are 208 and 160 MeV, respectively. The LET values and range were calculated in the stopping and range of ions in matter (SRIM). In these experiments, the fluxes of ions are set values (Table 3). There is a certain degree of deviation between set values and actual heavy ion experiments. During the heavy ion irradiation experiments, the p-GaN HEMTs were fixed in the vacuum tank, and the heavy ion beam irradiated the surfaces of devices vertically. Figure 1(d) shows the picture of the vacuum tank used in the heavy ion irradiation experiment.

Table 2 Characteristics of the ion species used in this work

Ion species	Energy (MeV)	LET@GaN (MeV·cm^2/mg)	Range@GaN (μm)	Fluence (n/cm^2)
Ge	208	28.51	16.10	1.24×10^6
Cl	160	10.04	23.63	1.31×10^6

Table 3 Summary of experimental results

Maximum qualified voltage (V)	Failure voltage (V)	Ion species	Flux (n/(cm^2·s))	Fluence (n/cm^2)
500	600	Ge	15000	1.24×10^6
500	580	Ge	15000	1.34×10^6
200	300	Ge	15000	7.02×10^5
200	300	Cl	15000	1.24×10^6
400	500	Cl	10000	1.31×10^6
–	100	Cl	9500	1.84×10^5

The ions fluxes were set to be a constant value. The voltages of gate electrodes (V_{G}) were applied to 0 V (off-state), source electrodes of devices were grounded, and voltages of drain electrodes (V_{D}) increased gradually from 100 V. The value of V_{D} was increased by 100 V until the ion fluence reached 2.410^5 n/cm^2. The tests were stopped when the total ion fluence reached 2.0×10^6 n/cm^2, or the leakage currents of the devices reached 100 mA. The device was considered to be broken down while the leakage current reached 100 mA [17].

The six groups of samples were irradiated in the heavy ion irradiation experiments. Table 3 presents the experimental results. Maximum qualified voltage is the maximum drain electrode voltage (V_{D}) of the device that could work in the heavy ion irradiation environment. The device was considered to be broken down while the leakage current reached 100 mA. Failure voltage is the voltage applied to the drain electrode when the device breaks down. By performing the two kinds of heavy ion irradiation experiments, we found that the variation of flux has little effect on GaN HEMTs. The failure of GaN HEMTs is random under different fluxes and mainly related to operating voltages under heavy ion irradiation.

3 Results and discuccion

Samples with higher qualified voltages were selected for the analysis. Figure 2 shows the current variation of the devices under different V_{D} during heavy ion irradiation. The off-state leakage currents of the device are 1.97/3.45/4.22/4.88/5.00 A, with the V_{D} of 100/200/300/400/500 V for Ge ion irradiation, respectively. The corresponding values are 1.07/1.82/3.20/4.80 A, with the V_{D} of 100/200/300/400 V for Cl ion irradiation. Ge ion-irradiated device was broken down while $V_{\mathrm{D}} = 600$ V and fluence = 1.24 $\times10^6$ n/cm^2. The corresponding values of Cl ion-irradiated devices were 500 V and 1.31×10^6 n/cm^2. The failure mechanism of the two irradiated devices is analyzed as follows.

Figure 3 shows the output and transfer characteristics of the p-GaN HEMTs before and after heave ions irradiation. The commercial p-GaN HEMTs possess large W_G and output current. To avoid the self-heating effect, pulse I-V measurements were adopted to characterize the output current of the irradiated devices. The pulsed width is 200 μs, and the pulsed period is 20 ms. As shown in Figure 3(a), the I_{Dmax} of GaN HEMTs is above 30 A. There is no obvious decrease in I_{Dmax} for the GaN HEMTs observed after Ge and Cl ion irradiation. As shown in Figure 3(d), the variation of V_{TH} for GaN HEMTs is small after Ge and Cl ion irradiation. However, the off-state leakage currents of GaN HEMTs increase after ions irradiation. The $I_{\mathrm{D,leakage}}$ under off-state increases from 1.8×10^{-9} to $1.1\times10^{-5}/4.2\times10^{-3}$ A for GaN HEMTs after Ge and Cl ion irradiation, respectively.

The source, gate, and drain leakage currents of the p-GaN HEMTs under off-state were monitored before and after Ge/Cl ions irradiation. As shown in Figure 4, I_{S}, I_{D}, and I_{G} were simultaneously monitored with V_{D} swept from 0 to 600 V. Before heavy ion irradiation, I_{S} of GaN HEMTs was as low as 76 nA when V_{D} was 600 V. However, I_{D} and I_{G} increased with increasing V_{D}. These two leakage currents reached 6.22 and 6.59 μA, respectively, when V_{D} was 600 V. The leakage path between the gate and drain electrodes is the main reason for drain leakage current before heavy ion irradiation. The $\mathrm{BV}_{\mathrm{DS}}$ of the devices decreased sharply to 18.4 and 30.1 V, respectively, after Ge and Cl ion irradiation. At the moment that the devices were broken down, the I_{GS} of GaN HEMT were as low as 0.62 and 0.65 μA after Ge and Cl ion irradiation, whereas the I_{D} rapidly increased to 1 A. The new leakage path was generated

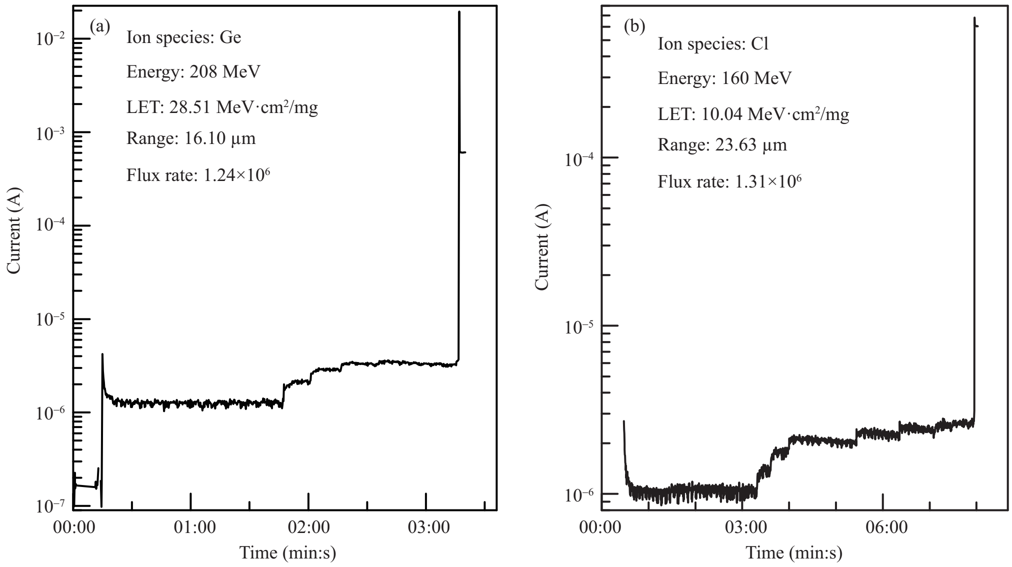

Figure 2 Variation of the drain leakage currents during (a) Ge and (b) Cl ions irradiation.

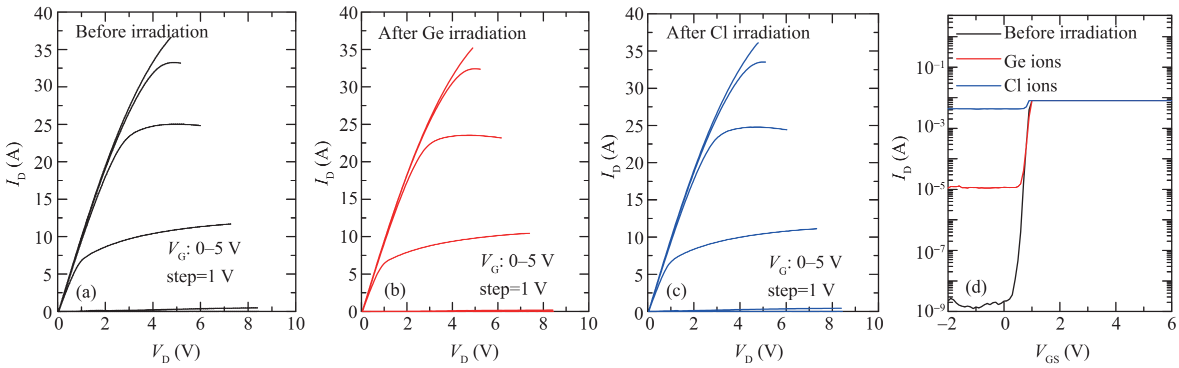

Figure 3 (Color online) Output characteristics of GaN HEMTs (a) before heave ions irradiation, after (b) Ge and (c) Cl ions irradiation. (d) Transfer characteristics of the GaN HEMTs before and after heave ions irradiation.

between source and drain electrodes after Ge/Cl ions irradiation [18–20]. The degradation of irradiated p-GaN HEMTs results from the defect percolation process between source and drain electrodes instead of the leakage path between the gate and drain electrodes.

Figure 5 shows the variations of the forward and reverse gate leakage currents after heavy ion irradiation. As shown in Figure 5(a), the forward gate leakage currents of p-GaN HEMTs are 8.63/6.99 μA ($V_{\rm G}$ = 4 V) after Ge/Cl ion irradiation. However, it is slightly greater than the value of 4.11 μA before heavy ions irradiation. As shown in Figure 5(b), the reverse gate leakage current are 33.9/29.1 nA ($V_{\rm G}$ = −10 V) after Ge/Cl ions irradiation, respectively. Compared with the increase in $I_{\rm D}$, the corresponding values of forward and reverse gate leakage currents are negligible. The slight variation of $I_{\rm G}$ indicates that the irradiation of Ge/Cl ions did not significantly affect the Schottky gate contact. Although heavy ion irradiation may introduce some trap states under the gate electrode, heavy ion irradiation did not generate an obvious leakage path under the gate electrode.

Figure 6 shows the frequency-dependent C-V hysteresis loop of GaN HEMTs before and after Ge/Cl ion irradiation. The frequency-dependent C-V measurements start from biasing the gate electrode from depletion to accumulation with a step of 0.01 V and then sweeping back to depletion. Trap states located under the gate electrode may trap and detrap electrons at these bidirectional sweeps. This feature leads to a shift of the flat-band voltage ($V_{\rm FB}$) during the C-V measurement. The C-V hysteresis values are both 0.05 V before and after Ge/Cl ion irradiation. It means that the trap states under the gate electrode do not change significantly after Ge/Cl ion irradiation.

Figure 7 shows the variation of the capacitance of GaN HEMTs with frequency under a different $V_{\rm G}$ [21]. For a certain $V_{\rm G}$, the capacitance decreases with an increasing frequency, and the frequency

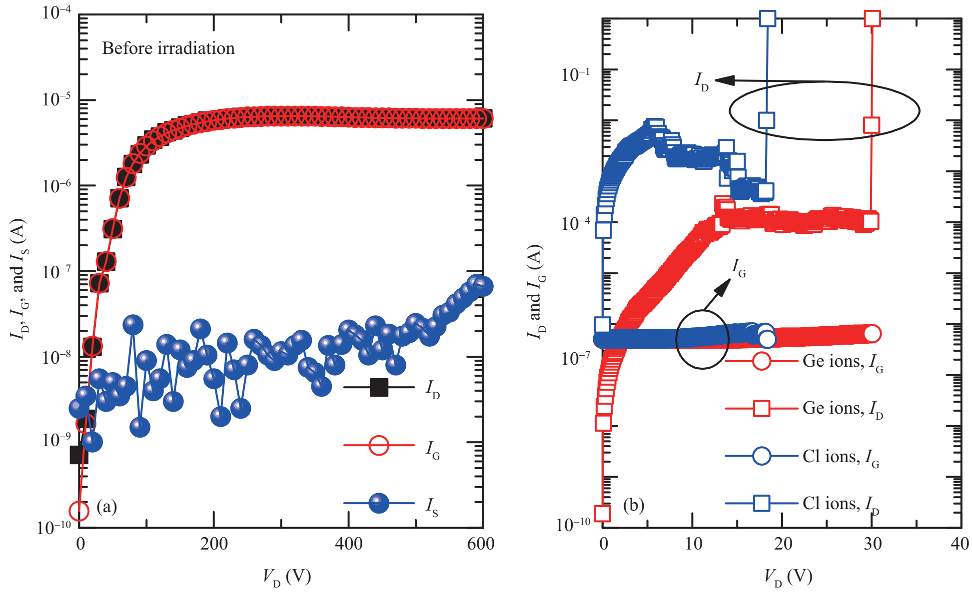

Figure 4 (Color online) (a) I_S, I_D, and I_G of GaN HEMTs under the off state before heavy ions irradiation; (b) I_D and I_G of GaN HEMTs under the off state after Ge/Cl ions irradiation.

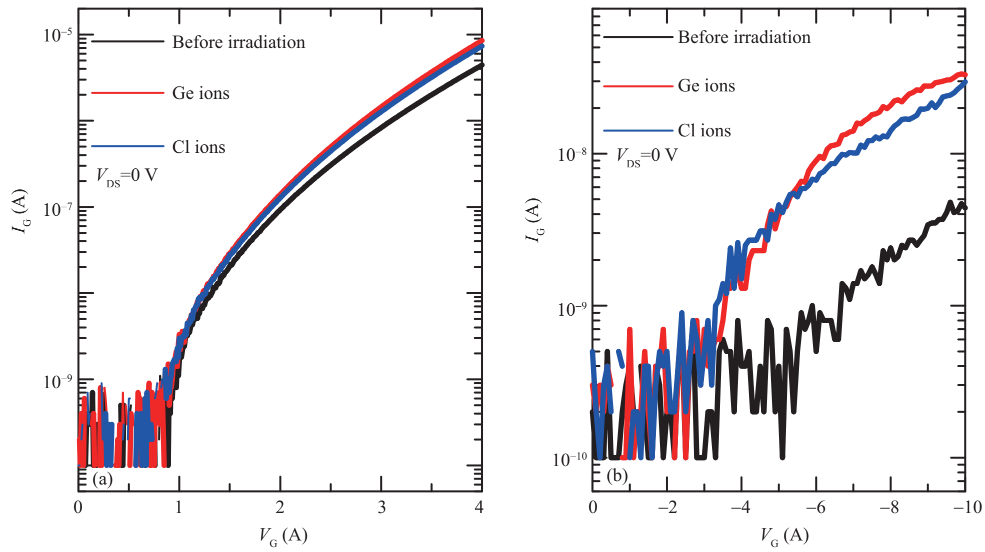

Figure 5 (Color online) The variation of (a) forward and (b) reverse gate leakage currents characteristics.

response flats over the entire range (1 kHz–1 MHz). Since the p-n junction structure existed below the gate electrode for p-GaN HEMTs, the depletion region width of the p-n junction reduces with an increase in V_G. The phenomenon decreases the capacitance slightly with an increasing frequency for V_G = 0.8–1.0 V and significantly decreases for V_G = 1.0–1.4 V. The rate of frequency response is slower, and the capacitance is slightly larger for Ge/Cl ion-irradiated GaN devices. It can be speculated that a small number of trap states were induced under the gate electrode after Ge/Cl ion irradiation.

Figure 8 shows the high-resolution transmission electron microscope (TEM) photographs of the cross-section of the irradiated p-GaN HEMTs to further investigate the failure mechanism of GaN HEMTs of heavy ion irradiation. The line-shaped crystal defects extending from the surface of the GaN material into the buffer layer were introduced using heavy ion irradiation, and other defects such as dislocation were extending from the nucleating to the buffer layer. The gate region is marked by red boxes in Figure 8(a). The crystal defects under the gate electrode were marked by the red box in Figures 8(b)–(e) for different resolutions. The marked crystal defects are small parts of the lattice defects observed on this cross-section. The irradiation-related crystal defects can also be found between the gate and drain electron

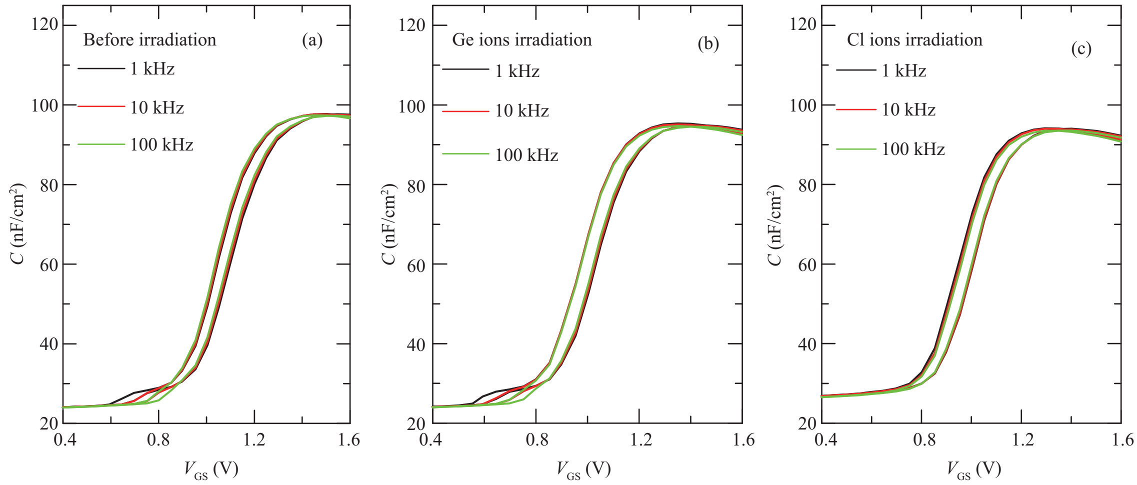

Figure 6 (Color online) The frequency-dependent C-V hysteresis loop of GaN HEMTs (a) before irradiation, after (b) Ge and (c) Cl ions irradiation.

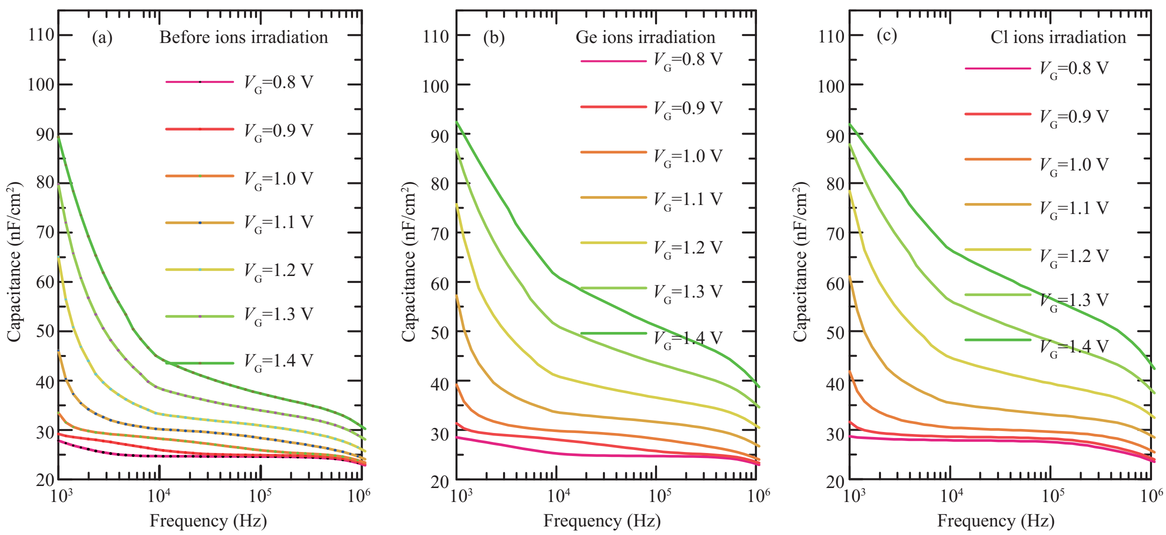

Figure 7 (Color online) The variation of capacitance of GaN HEMTs with frequency under different gate voltages (a) before irradiation, after (b) Ge and (c) Cl ions irradiation.

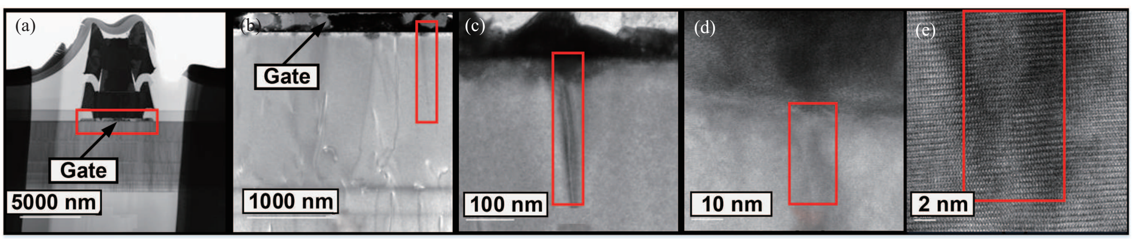

Figure 8 (Color online) The high-resolution TEM photographs of the cross section of GaN HEMTs after heave ions irradiation. The resolutions of the TEM photographs are (a) 5000 nm, (b) 1000 nm, (c) 100 nm, (d) 10 nm, and (e) 2 nm, respectively.

beside the gate region. Many line-shaped crystal defects extend from the surface of the GaN material into the buffer layer. Since the resolution increased to 100/10/2 nm, the angstrom morphology of crystal defects after heavy ion irradiation can be observed. Combined with the variation of leakage currents after heavy ion irradiation, the buffer layers of the irradiated devices were damaged, and a leakage path may be generated in the buffer layer, significantly increasing the source and drain leakage currents. Around the range of line-shaped crystal defects, a large number of electron-hole pairs may be generated under a high electric field. However, the variation of trap states under the gate electrode is negligible, and the gate leakage currents increase slightly. The defect percolation process in the buffer layer is the dominant factor of irradiated GaN device failure.

4 Conclusion

In this study, we conducted heavy ion experiments on 650 V p-GaN normally-off HEMTs using Ge and Cl ions. We used *I-V* and *C-V* characteristic curves and TEM to investigate the failure mechanism of irradiated GaN devices. After Ge/Cl ion irradiation, $I_{\mathrm{G,reverse}}$ increased from 4.9×10^{-9} to $3.39\times10^{-8}/2.91\times10^{-8}$ A ($V_{\mathrm{G}} = -10$ V) respectively, and $I_{\mathrm{D,leakage}}$ increased from 1.8×10^{-9} to $1.1\times10^{-5}/4.2\times10^{-3}$ A under off-state, respectively. Additionally, many line-shaped crystal defects were captured using TEM. The leakage path generated in the buffer layer is the dominant factor of irradiated GaN device failure.

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