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The effects of ^{60}Co γ-ray irradiation on the DC characteristics of enhancement-mode AlGaN/GaN high-electron-mobility transistors*

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The effects of ^{60}Co γ-ray irradiation on the DC characteristics of AlGaN/GaN enhancement-mode high-electron-mobility transistors (E-mode HEMTs) are investigated. The results show that having been irradiated by ^{60}Co γ-rays at a dose of 3 Mrad (Si), the E-mode HEMT reduces its saturation drain current and maximal transconductance by 6% and 5%, respectively, and significantly increases both forward and reverse gate currents, while its threshold voltage is affected only slightly. The obvious performance degradation of E-mode AlGaN/GaN HEMTs is consistent with the creation of electronegative surface state charges in the source-gate spacer and gate-drain spacer after being irradiated.

Keywords: AlGaN/GaN, enhancement-mode high-electron-mobility transistors, ^{60}Co γ-ray irradiation

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1. Introduction

Enhancement-mode (E-mode) AlGaN/GaN high-electron-mobility transistors (HEMTs) are desirable in microwave amplifiers, high power switches, and high-temperature integrated circuits (ICs).[1] They can not only reduce circuit complexity, but also improve system safety and stability. A novel fluoride-based plasma treatment is a robust process to realize E-mode AlGaN/GaN HEMTs.[2–5] The plasma treatment can effectively incorporate negatively charged fluorine ions into the AlGaN barrier and positively shift the threshold voltage. In the last few years, top groups from all over the world have extensively studied the effects of ^{60}Co γ-ray irradiation on conventional depletion-mode (D-mode) AlGaN/GaN HEMTs.[6–11] However, there has been little research on the radiation reliability[12] of fluorine plasma treatment E-mode AlGaN/GaN HEMTs and the methods to improve its radiation hardness.[13]

In the present paper, we realize normally-off AlGaN/GaN HEMT devices by using fluoride-based plasma treatment. An E-mode AlGaN/GaN HEMT is exposed to ^{60}Co γ-rays at a dose of 3 Mrad (Si). Its saturation drain current (I_{dsat}) and the maximal transconductance (g_{mmax}) of the E-mode HEMT are reduced and its forward and reverse gate currents are increased, while its threshold voltage is affected only slightly. The degradation is consistent with the γ-ray irradiation that induces electronegative surface state charges in the source–gate spacer and gate–drain spacer at low dose (3 Mrad).[14]

2. Experiment

The AlGaN/GaN HEMT structure used in this paper consists of a 2-μm undoped GaN, and a 30 nm $Al_{0.25}Ga_{0.75}N$ grown sequentially on sapphire by metal-organic-chemical vapor deposition (MOCVD). The device, with a gate length of 3 μm and gate width of 120 μm, was fabricated in the following FET fabrication steps. Ohmic contacts were prepared by an electron beam evaporating a multilayered Ti/Al/Ti/Au (20 nm/50 nm/40 nm/50 nm) sequence followed by rapid thermal annealing at 825 °C for 30 s in nitrogen ambient. Device isolation was achieved via boron ion implantation. The ohmic contact resistance of 0.62 Ω·mm and specific contact resistivity of 6.3×10^{-3} Ω·cm^2 were measured with the transmission-line method. After the gate positions

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were defined by photoresistivity, the samples were treated by CF_4 plasma in a reactive ion etching (RIE) system at a radio frequency (RF) plasma power of 60 W for 300 s. The Ni/Au (100 nm/50 nm) metals were e-beam evaporated and lifted off to form gate electrodes. Finally, post-gate annealing was conducted at 450 °C for 10 min in nitrogen to repair the implantation-induced damage in the AlGaN barrier and channel.

The fabricated device was exposed to a ^{60}Co γ-ray source at room temperature for an accumulated dose of 3 Mrad (Si) and flux of 1.5109 Gy/s (Si). All measurements were made within 30 min after irradiation at room temperature by an HP 4155B.

3. Results and discussion

Figure 1 shows the transfer characteristics of the E-mode HEMT before and after ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si). From this figure, it can be seen that after ^{60}Co γ-ray irradiation at a dose of 3 Mrad, $I_{\rm dsat}$ and $g_{\rm mmax}$ almost decrease by 6% ($V_{\rm gs}$ = 5) and 5%, while the threshold voltage ($V_{\rm th}$) remains relatively unaffected. However, the changes in $I_{\rm dsat}$ and $g_{\rm mmax}$ are different from those shown by Gu *et al.*,[11] who found that the exposure to ^{60}Co γ-ray irradiation of 1.6 Mrad (Si) could cause the electron mobility to recover after fluorine plasma treatment and the $I_{\rm dsat}$ and $g_{\rm mmax}$ to increase.[11] The structural ordering of native defects is possible. A larger dose of ^{60}Co γ-ray irradiation does not restore the damage from fluorine plasma treatment, but it induces deterioration by γ-irradiation. The degradation is caused mainly by the creation of electronegative surface state charges in the source-gate spacer and gate-drain spacer at low dose (3 Mrad). The source, drain, and gate regions are protected by metal electrodes from ^{60}Co γ-ray irradiation, while the source–gate spacer and the gate–drain spacer are exposed to ^{60}Co γ-ray irradiation directly, which creates electronegative surface state charges. These electronegative surface state charges lead the two-dimensional electron gas (2DEG) under the source–gate spacer and the gate–drain spacer to be depleted to a certain extent, and the total 2DEG density ($n_{\rm s}$) to be reduced greatly. The electronegative surface charges also increase the gate–source resistance ($R_{\rm gs}$) and gate–drain resistance ($R_{\rm gd}$). The reduction in $n_{\rm s}$ and the increases in $R_{\rm gs}$ and $R_{\rm gd}$ bring about an obvious decrease in $I_{\rm dsat}$ ($V_{\rm gs}$ = 5 V). Since $g_{\rm m} = \partial I_{\rm ds}/\partial V_{\rm gs}$, the decrease originates from the reduced drain-source current ($I_{\rm ds}$). Indeed, in an ideal HEMT transistor model, the shift of threshold voltage ($\Delta V_{\rm th}$) will be entirely determined by changing the sheet density of the total charges ($\Delta\sigma$) in a barrier of width (d), i.e., $\Delta V_{\rm th} = \Delta\sigma d/\varepsilon$. However, low dose (3 Mrad) ^{60}Co γ-ray irradiation could not create a sufficient number of traps to significantly change the density of the total charges.[8] Furthermore, due to protection from the gate electrode, the region under the gate is virtually unaffected during the exposure to ^{60}Co γ-ray irradiation, which keeps $V_{\rm th}$ almost unaffected.

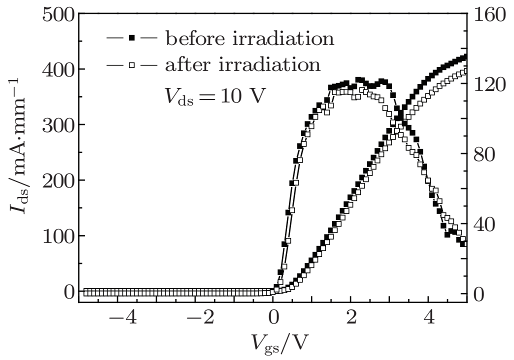

Fig. 1. The $I_{\rm ds}$–$V_{\rm gs}$ characteristics of an E-mode HEMT before and after ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si).

Figure 2 shows the output characteristics of an E-mode HEMT before and after ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si). From Fig. 2, we can find that $I_{\rm dsat}$ has slight changes at low gate voltages (−1 V ∼ 0.5 V), and obvious degradations at a higher gate voltage ($V_{\rm gs}$ = 2 V). At low gate bias (when $V_{\rm gs}$ almost equals $V_{\rm th}$), the source resistance and the drain resistance ($R_{\rm sd}$) are mainly determined by the channel resistance under the gate, while they are mainly determined by $R_{\rm gd}$ and $R_{\rm gs}$ at high gate bias. The ^{60}Co γ-ray irradiation enhances $R_{\rm gd}$ and $R_{\rm gs}$ significantly, but only affects the channel resistance under the gate slightly. This is consistent with the transfer characteristics depicted in Fig. 2.

Figure 3 shows the forward and reverse gate leakage characteristics of an E-mode HEMT before and after ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si). It can be seen that the forward and reverse gate leakage both obviously increase after ^{60}Co γ-ray irradiation. On the one hand, because of the creation of electronegative surface charges, the surface leakage between the gate and source is enhanced significantly. On the other hand, the creation of trap charges on the AlGaN surface after ^{60}Co γ-ray irradiation will deteriorate the perfectness of the crystalline structure of the AlGaN layer under γ-ray irradiation. This disadvantage in crystalline structure results in the deterioration of the

AlGaN barrier height. Therefore, the Schottky characteristics degrade after ^{60}Co γ-ray irradiation, which is consistent with Fig. 3.

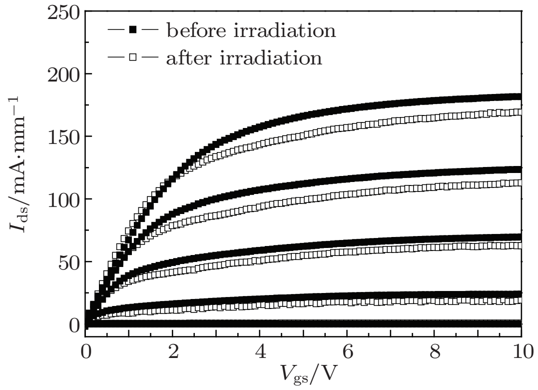

Fig. 2. The I_{ds}–V_{ds} characteristics of an E-mode HEMT before and after ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si). The value of V_{gs} is between −1 V and 2 V, with a step of 0.5 V.

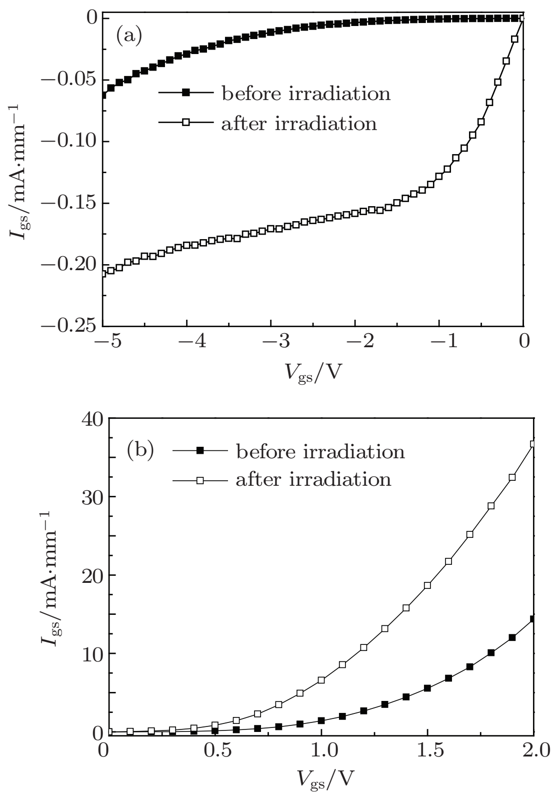

Fig. 3. (a) Forward gate leakage characteristics and (b) reverse gate leakage characteristics of E-mode HEMTs before and after ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si).

4. Conclusions

E-mode AlGaN/GaN HEMTs treated by fluorine plasma are fabricated and exposed to ^{60}Co γ-ray irradiation at a dose of 3 Mrad (Si). The DC performances, such as the I_{dsat} and g_{mmax} of the E-mode AlGaN/GaN HEMTs, degrade obviously after ^{60}Co γ-ray irradiation, and the gate leakage increases significantly, while V_{th} is changed only slightly. The degradation is due mainly to the creation of electronegative surface charges after ^{60}Co γ-ray irradiation.

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