^{60}Co γ-rays irradiation effect in DC performance of AlGaN/GaN high electron mobility transistors*

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Abstract: Unpassivated/passivated AlGaN/GaN high electron mobility transistors (HEMTs) were exposed to 1.25 MeV ^{60}Co γ-rays at a dose of 1 Mrad(Si). The saturation drain current of the unpassivated devices decreased by 15% at 1 Mrad γ-dose, and the maximal transconductance decreased by 9.1% under the same condition; moreover, either forward or reverse gate bias current was significantly increased, while the threshold voltage is relatively unaffected. By sharp contrast, the passivated devices showed scarcely any change in saturation drain current and maximal transconductance at the same γ dose. Based on the differences between the passivated HEMTs and unpassivated HEMTs, adding the *C*–*V* measurement results, the obviously parameter degradation of the unpassivated AlGaN/GaN HEMTs is believed to be caused by the creation of electronegative surface state charges in source–gate spacer and gate–drain spacer at the low dose (1 Mrad). These results reveal that the passivation is effective in reducing the effects of surface state charges induced by the ^{60}Co γ-rays irradiation, so the passivation is an effective reinforced approach.

Key words: AlGaN/GaN HEMTs; ^{60}Co γ-rays-irradiated; surface state
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1. Introduction

With wide energy bandgap, high electron saturation velocity, high breakdown fields, low thermal generation rates, AlGaN/GaN HEMTs are ideal for the development of electronic devices for high-temperature, high-power/voltage and high frequency environments[1–4]. Previous reports have shown that GaN-based electronic devices are considerably more radiation hard than their more conventional GaAs-based counterparts due to the higher displacement energy of the nitride materials[5]. So the GaN-based HEMTs will be a better candidate of devices for applications in outer space and other radiation environment, where devices must operate reliably when subjected to irradiations of protons, electrons, neutrons, or γ rays. The radiation resistance of AlGaN/GaN HEMTs has not been shown adequately because of material quality, technologic level of devices and structures of materials or devices, and so on. Therefore we need more research on the influence of radiation on materials and devices reliabilities.

In fact, ^{60}Co γ-rays irradiation of GaN-based materials and HEMTs has been reported[6–9]. Luo *et al.*[6] reported DC performance of ^{60}Co γ-rays-irradiated MBE-grown $Al_{0.2}Ga_{0.8}N$/GaN HEMTs, and they found the relatively obvious changes ($\leqslant$ 30%) in transconductance, drain current, and reverse breakdown voltage. Radiation-induced defects have been detected by deep-level transient spectroscopy (DLTS). The work of Long *et al.*[9] showed that radiation-induced heterointerface state charges also have influence of devices degradations.

In this work, we report on the effects of 1.25 MeV ^{60}Co γ-rays (up to 1 Mrad doses) on the DC characteristics of AlGaN/GaN HEMTs with two different devices structures (unpassivated and passivated). The ^{60}Co γ-rays irradiation effect is studied by means of *C*–*V* measurements and *I*–*V* measurements. Based on the analysis of the change in electronic characteristic of devices, the degradations of saturation drain current ($I_{\rm dsat}$), maximal transconductance ($g_{\rm mmax}$), threshold voltage ($V_{\rm th}$) and gate leakage current ($I_{\rm g}$) are presented and the physical mechanism of radiation damage is discussed in detail.

2. Devices and experiments

The AlGaN/GaN HEMT structures were grown by metallorganic chemical vapor deposition (MOCVD) developed by ourselves on (0001) sapphire substrates, and employed a 300 Å thick AlN buffer layer on sapphire substrates at 550 °C. Then 1.5 μm of undoped GaN was grown at 1040 °C, as well as 230 Å thick $Al_{0.3}Ga_{0.7}N$ barrier layer. It was composed of 60 Å undoped $Al_{0.3}Ga_{0.7}N$, 100 Å doped $Al_{0.3}Ga_{0.7}N$ (Si concentration = 2×10^{18} cm^{-3}) and 70 Å undoped $Al_{0.3}Ga_{0.7}N$. The samples contain an additional 10 Å AlN interlayer located between the $Al_{0.3}Ga_{0.7}N$ barrier and GaN channel to reduce alloy scattering. The processing involved lift

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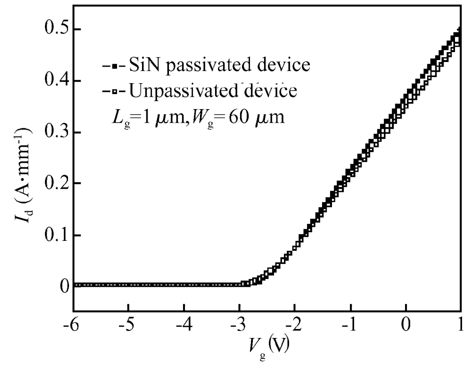

Fig. 1. I_d–V_d characteristics of 1×60 μm^2 SiN passivated and unpassivated AlGaN/GaN HEMTs before γ-irradiation.

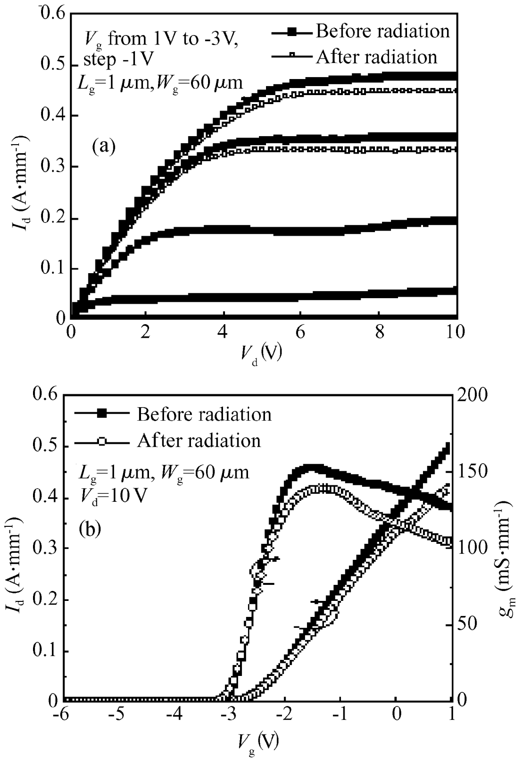

Fig. 2. (a) I_d–V_d and (b) I_d–V_g characteristics for 1×60 μm^2 unpassivated HEMTs before and after γ-irradiation to 1 Mrad dose.

off of electron beam evaporated Ti/Al/Ni/Au (20 nm/120 nm/55 nm/45 nm) for ohmic contacts or Ni/Au for Schottky gates. The ohmic metallization was annealed under N_2 at 830 °C for 30 s. The gate lengths (L_g) were 1 μm, with gate width (W_g) of 60 μm. The 50 nm SiN passivation was performed by employing PECVD. The measurement structures of *C*–*V* were made on the same materials as that of HEMTs, and they were in the round of devices regularly.

The devices were exposed to a ^{60}Co-γ source (1.25 MeV) for accumulated doses of 1 Mrad(Si) at 25 °C. The *C*–*V* characteristics were measured at 25 °C using a Keithley 590 *C*–*V* analyzer. The dc characteristics were measured at 25 °C using an HP 4156B parameter analyzer after irradiation for 30 min.

3. Results and discussion

Figure 1 shows the I_d–V_d characteristics of 1×60 μm^2 AlGaN/GaN HEMTs with SiN passivated and unpassivated before γ-irradiation. From Fig. 1 we can find that the drain current is decreased after the SiN passivated, but the amount is very little. So in this experiment, the SiN passivation affects the normal DC characteristics of HEMTs lightly; however, the effect of passivation on radiation is obvious, which will be discussed in detail.

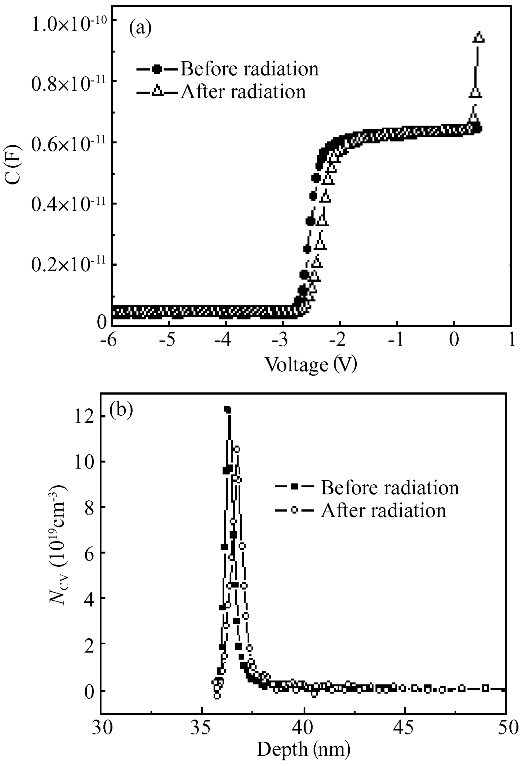

Fig. 3. (a) *C*–*V* characteristics of the AlGaN/GaN Schottky and (b) the heterointerface carrier distribution before and after γ-irradiation to 1 Mrad dose.

Figure 2 shows the I_d–V_d and I_d–V_g characteristics of an unpassivated AlGaN/GaN HEMT before and after the 1 Mrad γ-dose. From Fig. 2(a), we can find the I_{dsat} has hardly any degradation in the low gate bias region (V_g = −1, −2, −3 V) after irradiation, while the I_{dsat} is obviously decreased at higher gate voltage (V_g = 0, 1 V). This is consistent with the transfer characteristics in Fig. 2(b). After being irradiated with 1 Mrad γ-dose, the I_{dsat} (V_g = 1 V) is decreased by 15%, the g_{mmax} decreased by 9.1%, however, the V_{th} is relatively unaffected, which is completely different from the results of Luo *et al.*[6] and Long *et al.*[9]. There are several reasons that play roles in limiting the I_{dsat} in the AlGaN/GaN HEMTs. Theoretical calculation[10] shows that 2DEG density (n_s) and mobility of 2DEG (μ) are the dominant factors. So the degradation of the I_{dsat} is mostly attributed to the decrease of n_s or μ.

Approximately, we can get the carrier concentration (N_{cv}) versus the depletion region depth of the AlGaN/GaN HEMTs[11].

$$N_{CV} = -\frac{1}{q\varepsilon_0\varepsilon_{AlGaN}A^2}\,\frac{1}{\frac{dC^{-2}}{dV}}, \tag{1}$$

where ε_0 is the vacuum dielectric constant, ε_{AlGaN} is the AlGaN permittivity, and *A* is the Schottky area.

Figure 3 shows the *C*–*V* characteristics and the hetero-

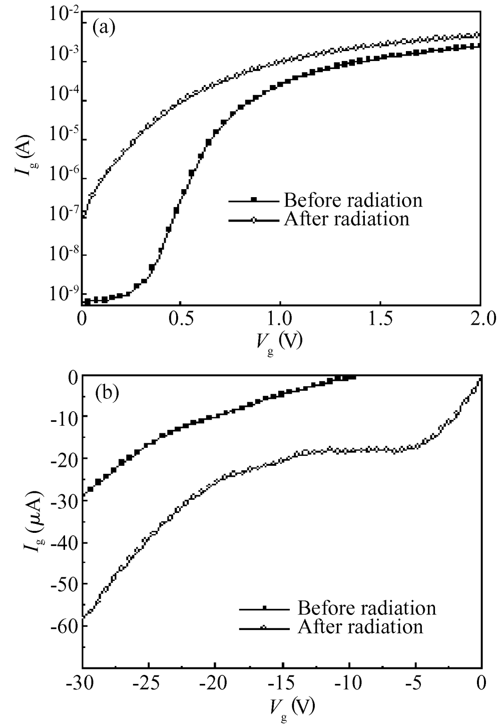

Fig. 4. (a) Forward gate characteristics and (b) reverse gate characteristics from 1×60 μm^2 unpassivated HEMTs before and after γ-irradiation to 1 Mrad dose.

interface carrier distribution of the unpassivated AlGaN/GaN Schottky before and after γ-irradiation to 1 Mrad dose. In Fig. 3(b), the x axis expresses the distance apart from AlGaN surface. At the positive bias voltage, the capacitance of the Schottky is increased sharply, which implies the increased forward gate leakage current after irradiation. Between –3 and –2 V, the slope of the C–V curve changes smaller after irradiation, which shows 2DEG distributing expanding to GaN. In Fig. 3(b), the peak value of carrier concentration has relevant decrease after irradiation due to the coincident decrease of n_{s}, and the position of peak value moves to GaN, which is consistent with the 2DEG distributing expanding to GaN in Fig. 3(a).

We can get the barrier height (Φ_{B}) versus the diode saturation current (I_{S}) of the gate Schottky characteristics as follows.

$$\Phi_{\mathrm{B}} = \frac{KT}{q} \ln\left(\frac{AA^{*}T^{2}}{I_{\mathrm{S}}}\right), \tag{2}$$

where K is Boltzmann's constant, T is the temperature, A is the Schottky area, and $A^{*} = 4\pi qk^{2}m^{*}/h^{3}$ is the Richardson's constant.

Figure 4 shows the forward gate Schottky characteristics and reverse gate Schottky characteristics of unpassivated HEMTs before and after the 1 Mrad-γ-irradiation. It can be seen the intercept of the forward gate Schottky characteristics at the y axis is increased after irradiation, which suggests the increase in the diode saturation current (I_{S}). So from Eq. (2), we can calculate that the Φ_{B} of gate Schottky diode shifts from a pre-irradiation value of about 0.679 to 0.633 eV at a dose of 1 Mrad. So the forward gate current is obviously increased after irradiation, which is completely different from the results of Luo *et al.*[6] that the forward gate leakage current is significantly decreased in the low bias region (< 0.5 V) where surface generation recombination is dominant and also at higher voltage, due to an increase in channel resistance. I think there are two reasons for the difference between our study and Luo *et al.*'s. On the one hand, the different structures, technologies and experiment conditions all could induce the different experiment results. On the other hand, under the radiation condition, the surface state of gate-drain spacer could assist electrons of channel tunneling into the gate electrode then forming gate leakage, namely these surface state charges could form an electric channel to increase the I_{gs}. Moreover, the barrier height is decreased because of the creation of trap charges on the AlGaN surface after radiation, and the decreased AlGaN barrier height could assist electrons of channel overcoming AlGaN barrier into the gate electrode then forming gate leakage. It can also be seen the reverse gate leakage current are obviously increased after irradiation as well. The increase of reverse gate leakage current implies the breakdown voltage become smaller. Anyway, the Schottky characteristic becomes degraded after γ-irradiation.

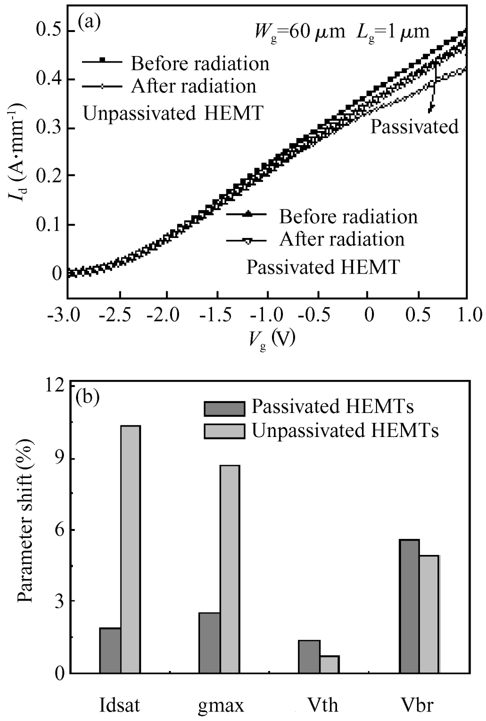

Fig. 5. (a) Transfer characteristics and (b) parameters shift of passivated HEMTs and unpassivated HEMTs after γ-irradiation to 1 Mrad dose.

Figure 5 shows the transfer characteristics and parameters shift of the passivated HEMTs or unpassivated HEMTs after γ-irradiation to 1 Mrad dose. Both the I_{dsat} and $g_{\max}$ are degraded to a certain extent for the unpassivated HEMTs. While for the passivated HEMTs, not only the I_{dsat} but also the $g_{\max}$ shows scarcely any change even the dose up to 1 Mrad, and only the breakdown characteristics changes which is attributed to the degradation of the gate Schottky characteristic and the interface degradation of the passivation layer and the material.

The mechanism of 300 Mrad ^{60}Co γ irradiation induced

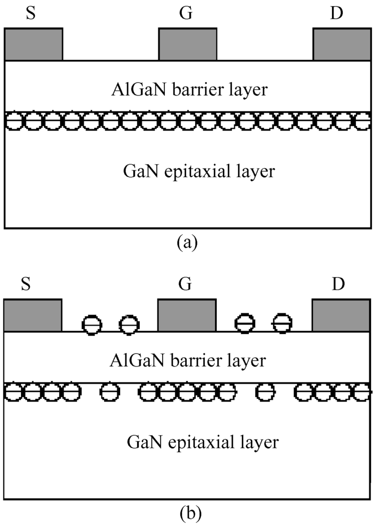

Fig. 6. Schematic diagram of effect of irradiation induced surface state on 2DEG in AlGaN/GaN HEMTs: (a) Before irradiation; (b) After irradiation.

2DEG transport property degradation has been explained by the irradiation induced heterointerface state charges in AlGaN/GaN HEMTs[9]. At the bigger fluence (the dose up to 600 Mrad), the shift of the device parameters has been attributed to the introduction of deep electron trapping states in AlGaN[6]. Because of the high displacement energy of the AlGaN and the GaN materials, only when the γ irradiation dose is up to 100 Mrad, the enough heterointerface states and the electron traps can be induced to affect device performance.

However, in our work, when the ^{60}Co γ-rays dose only up to 1 Mrad, both the $I_{\rm dsat}$ and $g_{\rm max}$ are degraded obviously for the unpassivated HEMTs. Because of the low dose (down to 1 Mrad), the heterointerface states do not change enough to degrade devices; moreover, the $V_{\rm th}$ is relatively unaffected after 1 Mrad dose γ-irradiation. So there are only a small number of trap defects formed, which has no obvious impact on the carrier density, and we should almost lose sight of the two factors above. In fact, by comparing the differences between passivated HEMTs and unpassivated HEMTs, and adding the *C–V* measurement results, we think the influence of the irradiation induced electronegative surface state charges are crucial reason for the unpassivated AlGaN/GaN HEMTs, which leads to the degradation of device characteristics.

Figure 6 shows the effect of irradiation induced electronegative surface state charges on 2DEG in AlGaN/GaN HEMTs. When ^{60}Co γ irradiation, the undersides of source electrode (S), drain electrode (D), and gate electrode (G) have hardly any effect due to screened by metal layers. While the unpassivated source-gate spacer (gd spacer) and gate-drain spacer (sg spacer) are direct exposure to ^{60}Co γ-rays irradiation, which induce many electronegative surface state charges consequently. These electronegative surface state charges could play a role in limiting the 2DEG under the sg and gd spacers. Contrarily, for the passivated AlGaN/GaN HEMTs, neither $n_{\rm s}$ nor μ of the 2DEG appears obvious degradation as a result of 2DEG materials having been protected by passivation layers. These also illuminate that if the surfaces of materials were exposed to the irradiation environments directly, it must be easy introducing the surface electron traps to affect electrons in channel.

In this study, $V_{\rm th}$ is hardly changed after the 1 Mrad γ-rays irradiation, because the $n_{\rm s}$ under the gate electrode is relatively unaffected. While the channel resistances of sg spacer ($R_{\rm gs}$) and gd spacer ($R_{\rm gd}$) increase due to the irradiation induced electronegative surface state charges, this makes source–drain on-resistance ($R_{\rm sd}$) increase, and leads to the decreased $I_{\rm dsat}$ sequentially. When the gate voltage ($V_{\rm g}$) is lower (approximately close to the $V_{\rm th}$), $R_{\rm sd}$ is mostly decided by the channel resistances under gate, and $R_{\rm gs}$ and $R_{\rm gd}$ occupy lower proportion in the whole $R_{\rm sd}$. So the $I_{\rm dsat}$ is affected little by the irradiation induced spacers 2DEG degradation. However, at the higher $V_{\rm g}$, the channel resistances under the gate become smaller, and the proportion of $R_{\rm gs}$ and $R_{\rm gd}$ becomes higher in the whole $R_{\rm sd}$, the $I_{\rm dsat}$ is affected more by the irradiation induced spacers 2DEG degradation. This is consistent with the less $I_{\rm dsat}$ degradation at lower $V_{\rm g}$ while the more $I_{\rm dsat}$ degradation at higher $V_{\rm g}$ in Fig. 2.

Moreover, after the γ-ray irradiation, the gate-drain surface leakage current ($I_{\rm gs}$) is significantly increased due to the irradiation induced electronegative surface state charges in sg and gd spacer. On the one hand, these surface state charges could assist electrons of channel tunneling into the gate electrode then forming gate leakage, namely these surface state charges could form an electric channel to increase the $I_{\rm gs}$. On the other hand, the creation of trap charges on the AlGaN surface could decrease the barrier height, and the decreased AlGaN barrier height could assist electrons of channel overcoming AlGaN barrier into the gate electrode to increase the leakage current of the Schottky. Therefore, both the forward and reverse gate characteristics of unpassivated HEMTs are obviously increased after 1 Mrad γ-irradiation, which is consistent with Fig. 4.

4. Conclusions

In conclusion, the crucial parameters such as $I_{\rm dsat}$ and $g_{\rm max}$ of the unpassivated AlGaN/GaN HEMTs are degraded obviously after 1 Mrad ^{60}Co γ irradiation, and either forward or reverse gate characteristics of the gate–drain diode is significantly increased, while the $V_{\rm th}$ is relatively unaffected. By sharp contrast, for the passivated AlGaN/GaN HEMTs, $I_{\rm dsat}$ and $g_{\rm max}$ show scarcely any change even the dose up to 1Mrad. The above study shows that the obviously parameters degradation of unpassivated AlGaN/GaN HEMTs is caused by the irradiation induced electronegative surface state charges in sg and gd spacers at the low dose (1 Mrad), and the passivation is effective in reducing the effects of surface state charges created by the ^{60}Co γ-rays irradiation, so the passivation is an effective reinforced approach.

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