^{60}Co gamma radiation effect on AlGaN/AlN/GaN HEMT devices

WANG Yan-Ping(王燕萍) LUO Yin-Hong(罗尹虹) WANG Wei(王伟) ZHANG Ke-Ying(张科营)
GUO Hong-Xia(郭红霞) GUO Xiao-Qiang(郭晓强) WANG Yuan-Ming(王园明)
Northwest Institute of Nuclear Technology, Xi'an 710024, China

Abstract: The testing techniques and experimental methods of the ^{60}Co gamma irradiation effect on AlGaN/AlN/GaN high electron mobility transistors (HEMTs) are established. The degradation of the electrical properties of the device under the actual radiation environment are analyzed theoretically, and studies of the total dose effects of gamma radiation on AlGaN/AlN/GaN HEMTs at three different radiation bias conditions are carried out. The degradation patterns of the main parameters of the AlGaN/AlN/GaN HEMTs at different doses are then investigated, and the device parameters that were sensitive to the gamma radiation induced damage and the total dose level induced device damage are obtained.

Key words: AlGaN/AlN/GaN HEMT, ^{60}Co gamma radiation, sensitive parameter

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1 Introduction

AlGaN/GaN heterostructures possess a wide energy band gap, high breakdown field, high saturated electron shift velocity, high thermal conductivity and a series of other excellent features, so HEMTs based on these GaN have been the subject of intensive research [1, 2]. The performance characteristics of HEMT devices make them very extensive and complex in their application fields and conditions. When HEMT devices work in a space environment or intense radiation field, the effect of high energy particle radiation should be considered, and therefore the radiation damage of the devices has to be studied.

More recently, researchers have been focusing on the study of the device performance degradation by gamma, proton, neutron and electron radiation on AlGaN/GaN HEMTs [3–14]. In 2002, Vituserich et al. [15] of Cornell University reported the influence of γ-ray irradiation on the device performance of AlGaN/GaN HEMTs, and found that when the radiation dose was relatively low at 10^5 rad(Si), the device parameters showed significant changes: the transconductance was reduced and the threshold voltage was changed to negative. Fan et al. [16] reported that at 300 Mrad, the influence was induced by ^{60}Co γ-ray irradiation on two-dimensional electron gas (2DEG) transport properties in AlGaN/GaN HEMTs, and considered that the device degradation was mainly due to the radiation induced heterojunction interface state charge. Luo et al. [4] also reported 600 Mrad ^{60}Co γ-rays on the DC characteristics of AlGaN/GaN HEMTs, and found little measurable change in the dc performance of the devices, which were observed at 300 Mrad. They believed that at 600 Mrad(Si), due to the introduction of deep electron traps by radiation, these carrier removal effects of the trap defects made the saturation drain current and transconductance peak of the device decrease by 30%. Umana-Membreno et al. [12] found that the reason for the device parameter degradation was the introduction of deep accept defects by radiation via measurements of deep level transient spectroscopy (DLTS). In order to increase the usability and reliability of GaN devices in a radiation environment, further study on the degradation pattern on the performance and the mechanism of radiation damage is necessary.

In this paper, we present the results of our study on the total dose effects of ^{60}Co gamma irradiation on AlGaN/AlN/GaN HEMTs in three different conditions. First, the ^{60}Co gamma irradiation experiment is briefly described. The effects of ^{60}Co gamma irradiation on the electrical characteristics of GaN HEMTs are then presented. The basic mechanisms of radiation effects and degradation patterns of radiation are subsequently discussed.

2 The experiment

2.1 Sample preparation

The sample is fabricated on the semi-insulating SiC substrate by mesa etches, source-drain and gate metallization, passivation, etc. The device structure consists of a GaN buffer layer on top of the SiC substrate, fol-

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lowed by an AlN interlayer, and capped by an AlGaN barrier layer. The gate length is 0.35 μm, and the gate width is 150 μm.

2.2 The experimental setting

The drain working voltage is 28 V for small gate width GaN power devices. In order to avoid the influence of self-heating and high electrical field stress effects on the device analysis, we select three irradiation bias conditions.

(1) Off-state: $V_{\rm DS}=8$ V; $V_{\rm GS}=-7$ V. (2) On-state: $V_{\rm DS}$=8 V; $V_{\rm GS}$=−2 V. (3) Floating.

Irradiation experiments were performed with a ^{60}Co source, and a UNIDOS dose meter was used to measure the dose. During the measurement, the radiation dose rate was 50 rad(Si)/s, and the total dose was 5×10^5, 1×10^6, 5×10^6 and 1×10^7 rad(Si), respectively. The performance parameters of the device were measured using an HP4156 semiconductor parameter analyzer before and after radiation.

2.3 Experimental results and analysis

1) Floating

Figures 1 and 2 show that the device transfer characteristics and drain source series resistance do not exhibit a measurable change at 10 Mrad(Si). When IDS1=10 mA, IDS2=20 mA, the voltages are VDS1 and VDS2, respectively, and the drain source series resistance $R_{\rm s}$=(VDS2−VDS1)/(IDS2−IDS1). The saturation drain current is slightly decreased, and the pinch-off leakage current is also decreased, which indicates that AlGaN/AlN/GaN HEMTs can have a high total dose level on floating.

2) On-state

Figures 3(a) and 4(a) show that a significant change in the slope of the curve appears when the radiation dose is up to 10 Mrad(Si), because an increasing heterojunction interface state charge leads to a decrease in the slope of the transfer characteristics curve, and the drain source series resistance increases. From Fig. 3(b) and Fig. 4(b), we can see that the saturation drain current is obviously decreased at low gate bias voltage ($V_{\rm G}$=−1, −2, −3 V) by increasing radiation dose, and this is consistent with the variation in the transfer characteristics in Fig. 3(a). The pinch-off leakage current is significantly reduced at 10 Mrad(Si), as compared with the current before radiation. It exhibits the change in the polarization bound charge of 2DEG or the concentration of effective ionized impurities in the AlGaN barrier layer, and the channel causes the shift in transfer characteristics.

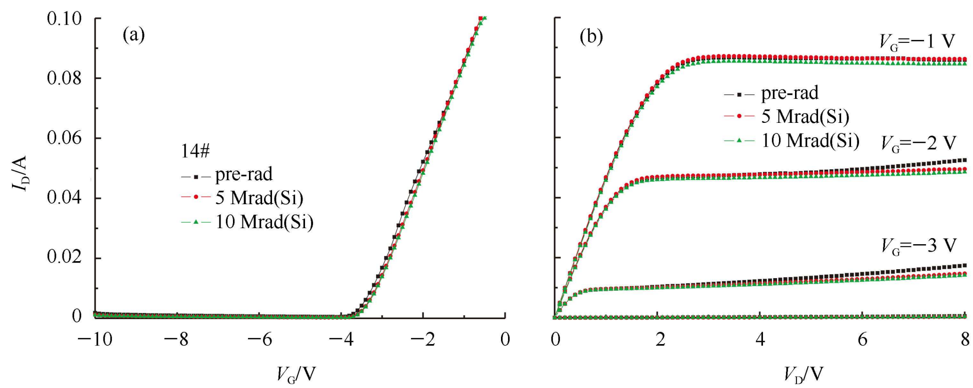

Fig. 1. (a) Transfer characteristics, and (b) output characteristics of HEMT devices before and after ^{60}Co γ-irradiation.

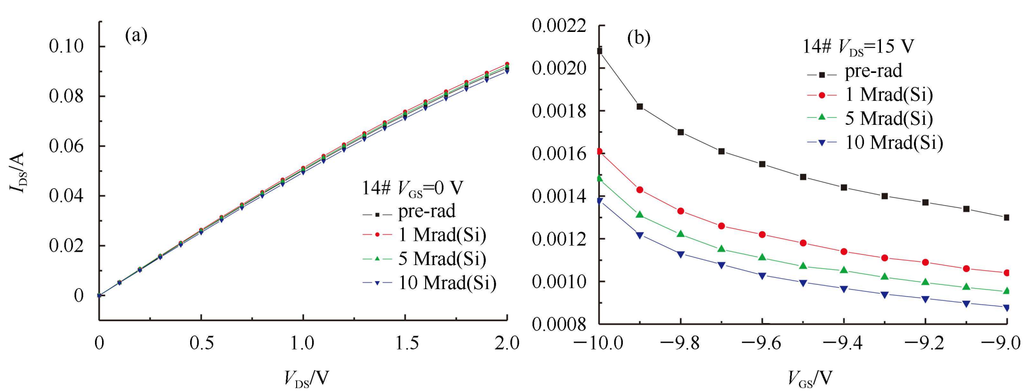

Fig. 2. (a) Series resistance, and (b) pinch-off leakage current of HEMT devices before and after ^{60}Co γ-irradiation.

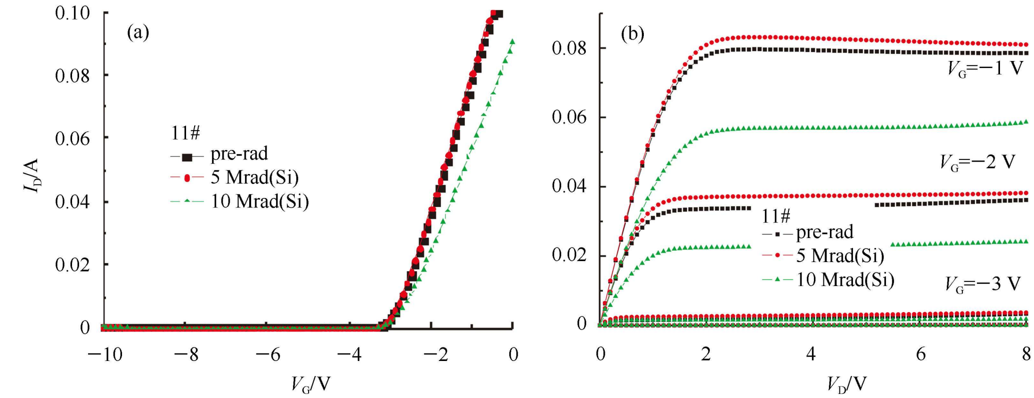

Fig. 3. (a) Transfer characteristics, and (b) output characteristics of HEMT devices before and after ^{60}Co γ-irradiation.

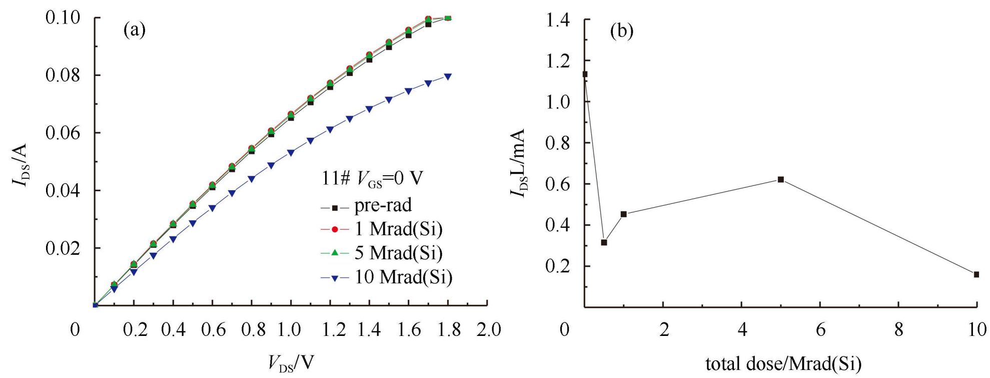

Fig. 4. (a) Series resistance, and (b) pinch-off leakage current of HEMT devices as a function of total dose before and after ^{60}Co γ-irradiation.

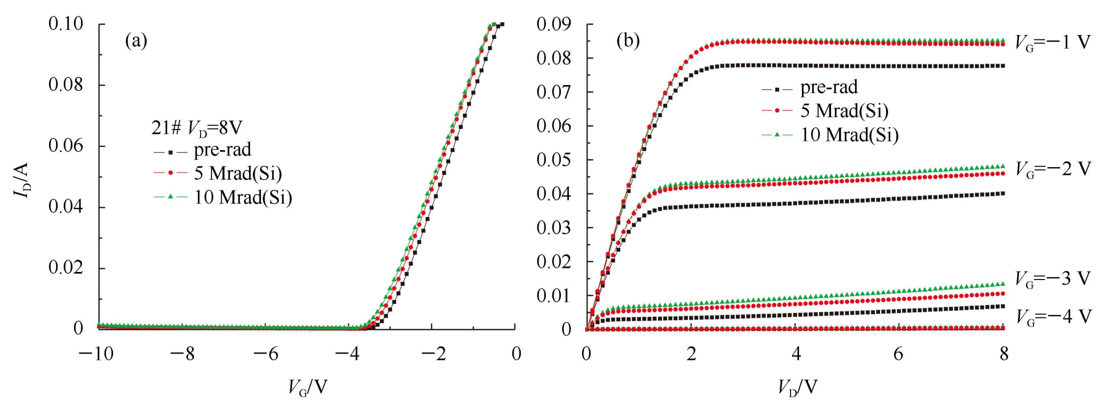

Fig. 5. (a) Transfer characteristics, and (b) output characteristics of HEMT devices before and after ^{60}Co γ-irradiation.

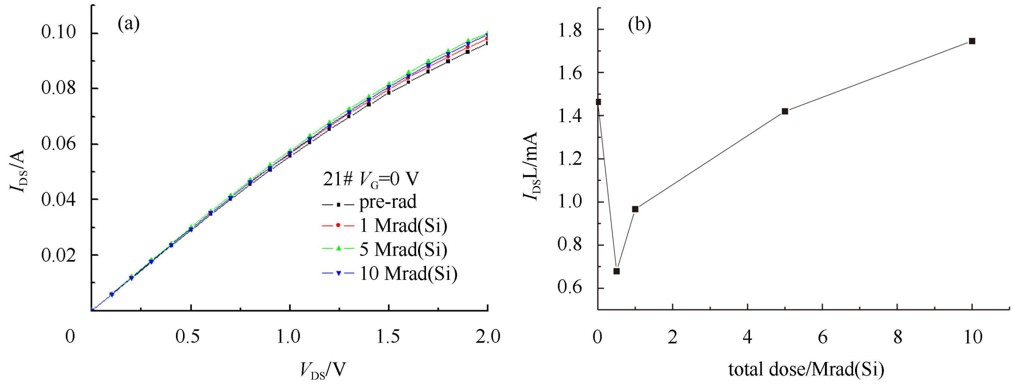

Fig. 6. (a) Series resistance, and (b) pinch-off leakage current of HEMT devices as a function of total dose before and after ^{60}Co γ-irradiation.

3) Off-state

Figure 5(a) shows that after off-state irradiation, the threshold voltage shifts slightly to negative, and the slope of the transfer characteristics curve does not exhibit a measurable change and shows a difference with the on-state. Fig. 5(b) shows that the saturation drain current is also significantly increased at constant V_G after irradiation, and the pinch-off leakage current is increased, but the source and drain series resistance do not exhibit a significant change.

3 Discussions

3.1 Mechanism of radiation damage

The change in I_{DS} and V_{TH} with γ dose indicates the influence of radiation degradation on HEMTs. I_{DS} can be described by the basic drain current model. For the heterojunction, radiation induces some defects on AlGaN, GaN and even in the passivation layer. The strong interface polarization effect on AlGaN/GaN creates high-density 2DEG [17, 18]. Formula (1) describes the effect of defects on 2DEG carrier concentration.

$$I_{DS} = -qWv(x)n_s(x), \tag{1}$$

where q is the elementary charge, W is the gate width and $v(x)$ is the mobility dependent on electron drift velocity, which changes with the channel electric field, up to the saturation electron velocity v_s. n_s is the sheet charge density. The change in carrier concentration n_s in the 2DEG and the change in mobility, which is related to the channel region $v(x)$, are two key parameters that are damaged by the radiation in the AlGaN layer. The equation for the carrier concentration is expressed as Formula (2), and the relativity of the threshold voltage is described in Formula (3).

$$n_s = \frac{\varepsilon(x)}{qd}\left(V_{GS} - \varphi_b(x) + \Delta E_C(x) + \frac{qN_d d^2}{2\varepsilon(x)} + \frac{\sigma(x)}{\varepsilon(x)} - \frac{E_F}{q}\right), \tag{2}$$

$$V_{TH}(x) = \varphi_b(x) - \Delta E_C(x) - \frac{qN_d d_d^2}{2\varepsilon(x)} - \frac{\sigma(x)}{\varepsilon(x)}, \tag{3}$$

where n_s is the sheet carrier density caused by the AlGaN doped layer, d is the distance between the gate and the sheet charge, V_{GS} is the gate-source voltage, $\varepsilon(x)$ is the dielectric constant of AlGaN, E_F is the Fermi level of the two-dimensional potential well, x is the Al molar component in AlGaN, N_d is the doping density in the AlGaN layer, d is the thickness of the AlGaN between the Schottky gate and the 2DEG, $\varphi_b(x)$ is the Schottky barrier height, $\Delta E_C(x)$ is the conduction band discontinuity, $\sigma(x)$ is the total sheet charge density and V_{TH} is the threshold voltage.

In order to identify what causes the current degradation, it is necessary to do radiation response analysis of each parameter. The Schottky barrier height $\varphi_b(x)$, the doping density in the AlGaN layer N_d, and the total sheet charge density $\sigma(x)$ could be the principal parameters affected by radiation. In the heterostructure, the radiation introduced deep-level traps and electron traps by captured carriers (the carrier removal effect) and the increased influence of trap-assisted tunneling will result in the changes in the effective donor doping density N_d in the AlGaN barrier layer. This also changes the effective barrier height $\varphi_b(x)$, and directly changes the 2DEG concentration in the GaN channel layer [19, 20]. Not only will these effects induce threshold voltage shift, drain current and transconductance degradation, but will also have a serious effect on gate characteristics. Thus it is one of the major mechanisms of radiation damage in HEMT devices.

Another major factor that affects the current output characteristics of HEMTs is the change in mobility. Due to the strong polarization effect and great conduction band discontinuity, there is a deep and narrow quantum well in the AlGaN/GaN heterostructures, in which the 2DEG concentration is high and the distribution is very close to the heterointerface [17, 18, 20]. This distribution will induce scattering effects of the interface state charge in the heterojunction more significantly. Considering the radiation degradation of mobility, the radiation induced interface-state plays a major role in AlGaN/GaN HEMTs degradation.

Furthermore, the series resistance is also a factor that can reduce the saturation drain current when radiation induces its change. The series resistance increase is induced by both the reduction in carrier concentration and the degradation in the mobility in the channel. Thus series resistance should be considered to contribute to drain current degradation.

3.2 Radiation damage mechanism analysis of the ^{60}Co source on GaN HEMTs

Based on the previous analysis of the degradation mechanisms of radiation damage, we analyzed the mechanism effect for ^{60}Co source experimental phenomena. This 2DEG is due to the spontaneous and piezoelectric polarization of GaN and AlGaN layers [17, 18]. On top of the AlN/GaN interface, a large conduction band discontinuity and the artificial doping of the heterojunction produces quite a high 2DEG density on GaN HEMT devices [17, 19]. In the radiation environment, radiation induces the semiconductor material heterojunction interface stress fracture, leading to the release of interface stress, the phenomenon of stress relaxation, and the stress induced piezoelectric polarization charge density to be reduced. This radiation induced interface stress relaxation will lead to a threshold voltage shift to positive, and the saturated drain current to drop, however, because of the AlGaN and GaN materials with strong chemical bonds and the high radiation threshold energy [3, 21], this effect can only be seen at and above 10 Mrad(Si). We studied the degradation of device performance at 5 Mrad(Si) and 10 Mrad(Si), respectively, as shown in Figs. 1 and 2. Both the saturation drain current and the pinch-off leakage current are slightly decreased; the device transfer characteristics and drain source series resistance do not exhibit a measurable change, which further demonstrates the excellent total dose level of these devices on floating.

Under the on-state irradiation bias conditions, the performance parameters of GaN devices show significant degradation. The slope of the transfer characteristics curve is reduced, and the output drain current and pinch-off leakage current are decreased. The shift in the transfer characteristic curve is induced by the polarization bound charge of 2DEG or the change in the effective ionized impurities concentration in the AlGaN barrier layer and channel. The heterojunction interface state charge increase can lead to the decrease in the slope of the transfer characteristics curve. Thus from these analyses, in the on-state radiation, the radiation can easily lead to the weak bond cleavage of the heterojunction interface of AlGaN/AlN/GaN, therefore forming radiation induced acceptor interface states. On the one hand, the increase in interface state charge will play a scattering center effect, leading to lower carrier mobility, and on the other hand, the acceptor interface states will capture an electron in the 2DEG and reduce the concentration of electrons in the 2DEG. Due to the source-drain series resistance, $(\mathrm{n}\mu)^{-1}$ is directly proportional. Then the series resistance increases, the saturation drain current is reduced, and the pinch-off leakage current decreases [18, 20].

On the off-state, the radiation induces ionization in the AlGaN barrier layer and then generates electron-hole pairs. Under the influence of off-state negative gate voltage, the electrons move to the heterojunction interface. Some electronics are incorporated into the 2DEG, and in the meantime a positive charge in the barrier layer increases the electron concentration in the 2DEG. These threshold voltage results slightly shift to negative and contribute a certain shielding effect on the gate voltage. This also affects the control of the gate for the channel carrier, and thus the saturation drain current increases. This phenomenon indicates that to some extent, the off-state radiation helps to improve device performance and increase output power.

4 Conclusions

Using the testing techniques and the experimental methods of the ^{60}Co gamma radiation effect, the studies of the total dose radiation effects on AlGaN/AlN/GaN HEMTs at three different irradiation bias conditions have been carried out. The degradation pattern of the main parameters of AlGaN/AlN/GaN HEMTs at different doses of γ-ray irradiation was investigated. These results show that the devices can have a high total dose level on floating; under the on-state irradiation bias conditions, the radiation induced heterojunction interface state is responsible for the decrease in saturation drain current and the slope variation of the transfer characteristics curve; at off-state, the radiation increased the concentration of captured positive charge in the AlGaN barrier layer, which leads to the increase in saturation drain current, and the shift in the threshold voltage to negative.

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