Neutron irradiation effects on AlGaN/GaN high electron mobility transistors*

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AlGaN/GaN high electron mobility transistors (HEMTs) were exposed to 1 MeV neutron irradiation at a neutron fluence of 1×10^{15} cm^{-2}. The dc characteristics of the devices, such as the drain saturation current and the maximum transconductance, decreased after neutron irradiation. The gate leakage currents increased obviously after neutron irradiation. However, the rf characteristics, such as the cut-off frequency and the maximum frequency, were hardly affected by neutron irradiation. The AlGaN/GaN heterojunctions have been employed for the better understanding of the degradation mechanism. It is shown in the Hall measurements and capacitance–voltage tests that the mobility and concentration of two-dimensional electron gas (2DEG) decreased after neutron irradiation. There was no evidence of the full-width at half-maximum of X-ray diffraction (XRD) rocking curve changing after irradiation, so the dislocation was not influenced by neutron irradiation. It is concluded that the point defects induced in AlGaN and GaN by neutron irradiation are the dominant mechanisms responsible for performance degradations of AlGaN/GaN HEMT devices.

Keywords: neutron irradiation, AlGaN/GaN high electron mobility transistor, heterojunction, defects

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1. Introduction

In recent years, the III–V nitrides, such as gallium nitride (GaN), have been viewed as highly promising for semiconductor device applications due to their direct, large band gap, high thermal and chemical stabilities. The AlGaN/GaN high electron mobility transistor (HEMT) is a prime candidate for high-power applications at microwave frequency. Compared with Si and GaAs-based devices, GaN-based devices are more radiation tolerant.[1] Because these devices are expected to work effectively in a space environment, the effects of radiation on these devices are important to consider.

Devices employed in space technology are exposed to both particles and electromagnetic radiation, such as electrons, protons, neutrons, and gamma rays.[2] Radiation effects include the effects of displacement damage and ionizing radiation. Earlier studies have shown that GaN-based materials and devices are mainly influenced by the displacement damage. Atoms will be displaced in crystal lattice and structural defects will be induced in semiconductor by the incident particles. Most research concentrates on the effects of proton radiation.[3] Neutron radiation effects in HEMTs have been reported by a few groups, but there is not a thorough understanding of the physical mechanism responsible for the degradation of electrical characteristics.[4] In what follows, we will discuss the effects of neutron irradiation on the electrical dc and rf properties of AlGaN/GaN HEMT devices, and then analyse the AlGaN/GaN heterojunctions in detail for the better understanding of the degradation mechanism.

2. Devices and experiments

The devices studied in this work were fabricated at Xidian University. 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

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fraction in AlGaN layer is 0.3. The fabrication processes of device 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 passivation. The gate length is 0.6 μm, and the gate width is 100 μm. The spontaneous and piezoelectric polarizations between AlGaN and GaN effectively result in polarization charge at the AlGaN/GaN interface. A high sheet carrier density two-dimensional electron gas (2DEG) can be formed, without intentional doping of the structure.

The AlGaN/GaN HEMT devices and heterojunction materials to be analysed were irradiated at room temperature by neutrons, whose energy is 1 MeV. The total neutronradiation fluence reached 1×10^{15} cm^{-2}. The dc and rf characteristics of these devices were measured at room temperature using an Agilent semiconductor parameter analyser. We also carefully investigated the AlGaN/GaN heterojunction due to the fact that it is the most important part in HEMT devices. The mobility and concentration of 2DEG before and after neutron irradiation have been tested by Hall measurements and capacitance–voltage C–V tests at room temperature. The material crystal quality has been investigated before and after irradiation by X-ray diffraction (XRD) ω–2θ rocking scans at room temperature.

3. Results and discussion

Figure 1 shows the output characteristics, the drain current ($I_{\rm ds}$) versus drain voltage ($V_{\rm ds}$) of AlGaN/GaN HEMT before and after neutron irradiation. It is seen that the saturation currents ($I_{\rm dsat}$) decrease after neutron irradiation. $I_{\rm dsat}$ decreases by 2% (−14.46 mA/mm) and 10% (−50.12 mA/mm) for gate voltage $V_{\rm gs} = 0$ V and $V_{\rm gs} = -2$ V respectively. This may be caused by either a decrease in electron concentration in the channel or a decrease in saturation carrier velocity. The slopes of the curves decrease at low bias, which indicates a decrease in the carrier mobility or concentration.

Figure 2 shows the transfer characteristics, the drain current $I_{\rm ds}$ versus gate voltage $V_{\rm gs}$ of AlGaN/GaN HEMT before and after neutron irradiation. They are measured at a drain voltage of 10 V. AlGaN/GaN HEMTs are in depletion-mode, so the threshold voltage ($V_{\rm th}$) is negative. The $V_{\rm th}$ shifts toward more positive values. The peak position of the transconductance ($G_{\rm m}$) curve does not shift after neutron irradiation. The maximum $G_{\rm m}$ decreases by 2% (−6.03 mS/mm) for the irradiated sample. However, the changes of both $G_{\rm m}$ and $V_{\rm th}$ are very small.

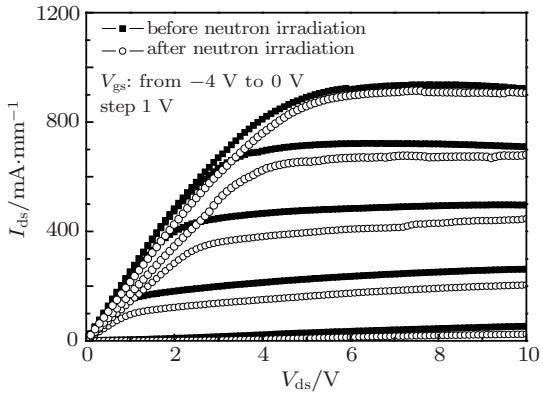


Fig. 1. $I_{\rm ds}$–$V_{\rm ds}$ characteristics of the AlGaN/GaN HEMT device before and after neutron irradiation.

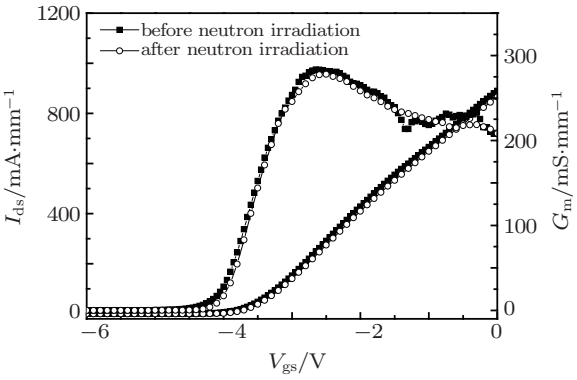


Fig. 2. Transfer characteristics of the AlGaN/GaN HEMT device before and after neutron irradiation.

Figure 3 shows the forward and reverse bias gate $I_{\rm g}$–$V_{\rm g}$ characteristics of AlGaN/GaN HEMTs before and after neutron irradiation. It is observed that neutron 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 $I_{\rm g}$–$V_{\rm g}$ characteristics. The barrier height is written as

$$\Phi_{\rm b}(x) = \frac{kT}{q} \ln\left(\frac{AA^*T^2}{I_{\rm s}}\right). \tag{1}$$

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

$$n = \frac{\lg e}{(kT/q)\,\text{slope}}. \tag{2}$$

We find that the Schottky barrier height decreases and the ideality factor increases significantly after neutron irradiation: the Schottky barrier height decreases from 0.61 to 0.58 eV; the ideality factor increases from 2.16 to 2.49. Defects induced by irradiation in the band gap and near the metal/AlGaN interface may act as tunneling sites, leading to the increase of gate current tunneling probability and the decrease of the Schottky barrier height.[5,6]

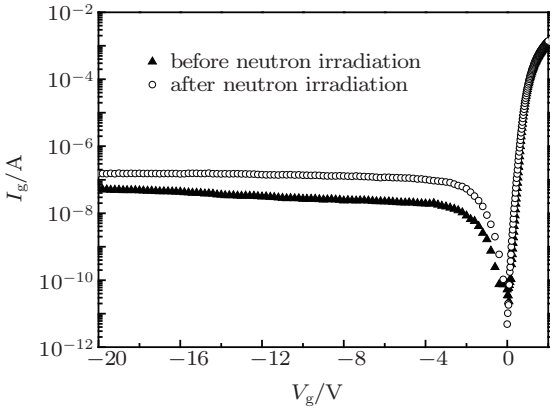


Fig. 3. I_g–V_g characteristics of the AlGaN/GaN HEMT device before and after neutron irradiation.

The rf measurement results are plotted in Fig. 4. There are little change in both the cut-off frequency (f_T) and maximum frequency (f_{max}). This is because the minority carrier lifetime is so short in GaN that the additional defect introduced does not appear to degrade it.[7]

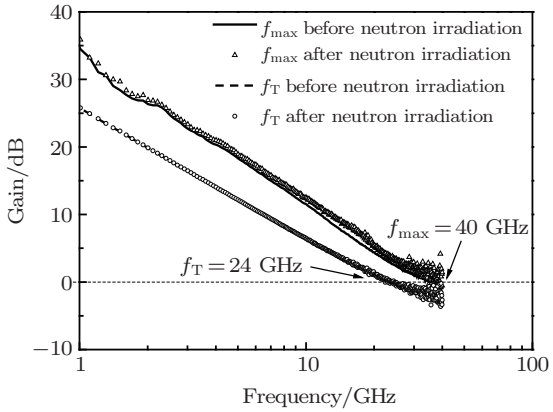


Fig. 4. The plots of f_T and f_{max} of the AlGaN/GaN HEMT device before and after neutron irradiation.

To evaluate the defect concentrations introduced by neutron radiation in the AlGaN/GaN HEMT devices, we also analysed the AlGaN/GaN heterojunction in detail. We performed Hall measurements on heterojunction before and after neutron irradiation at room temperature. The 2DEG concentration, mobility, and sheet resistance are shown in Table 1. The carrier concentration and mobility decrease after neutron irradiation, while sheet resistance increases.

Table 1. The degradation of Hall parameters of AlGaN/GaN heterostructure after neutron irradiation.

	Concentration/10^{13} cm^{-2}	Mobility/cm^2·V^{-1}·s^{-1}	Resistance/(Ω/sq)
Before irradiation	1.28	1673.79	292.44
After irradiation	1.02	1654.062	375.04

Figure 5 presents the results of high frequency (1 MHz) capacitance–voltage (C–V) measurements for AlGaN/GaN heterojunction before and after neutron irradiation. Compared with the electrical characterization of AlGaN/GaN HEMT devices, the shift of the V_{th} is more obvious in heterojunction material. This may be caused by the passivation which can suppress the electron trapping into the surface states during the neutron irradiation.[4]

It is seen in Fig. 5 that the threshold voltage shifts to a more positive value after neutron irradiation. Since the V_{th} shift is positive, we conclude that acceptor-like (negatively charged) traps are responsible for the threshold voltage shift. The increase in the acceptor concentration gives rise to larger depletion charge in the GaN and in turn increases the electric field at the interface modifying the triangular potential well.

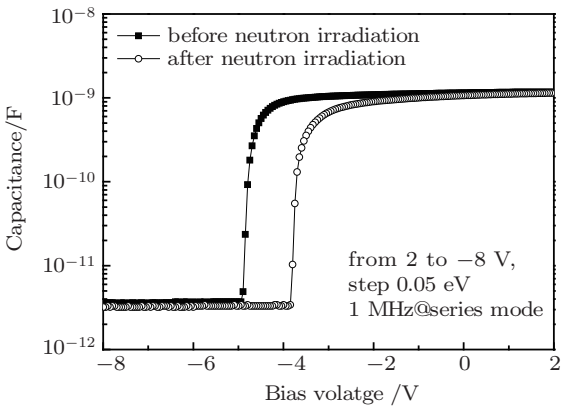


Fig. 5. The C–V characteristics measured at 1 MHz for AlGaN/GaN heterojunction before and after neutron irradiation.

The carrier concentration profiles were deduced from C–V measurements, as shown in Fig. 6. The maximum carrier concentration $N_{\rm cv}$ of AlGaN/GaN heterojunction changes from 3×10^{20} cm^{-3} to 3×10^{19} cm^{-3} after neutron irradiation, which indicates that the concentration of 2DEG decreases.

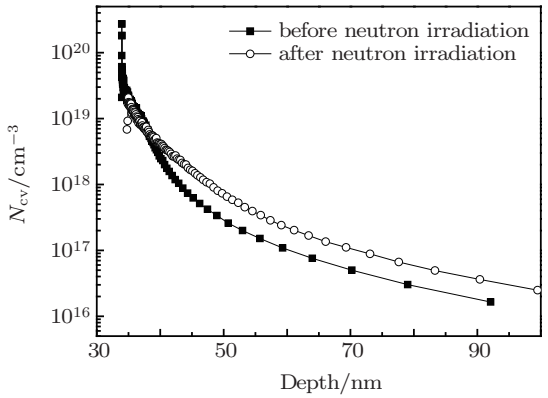


Fig. 6. Distribution of carrier concentration in AlGaN/GaN heterojunction deduced from C–V measurements before and after neutron irradiation.

It is well known that neutron irradiation can create two kinds of defects, i.e. dislocations and point defects. To investigate the crystal structure of the irradiated heterojunctions, XRD ω–2θ rocking scans in (0002) direction were made. Figure 7 shows the XRD spectra of samples before and after neutron irradiation. The peak position of the intensity is at 34.62° and the full width at half-maximum (FWHM) is about 0.1509 for the as-grown samples. The peak position of the intensity is at 34.63° and the FWHM is 0.1504 after neutron irradiation. They both change little, and this reflects that the dislocations in the samples are hardly affected by neutron irradiation.[8]

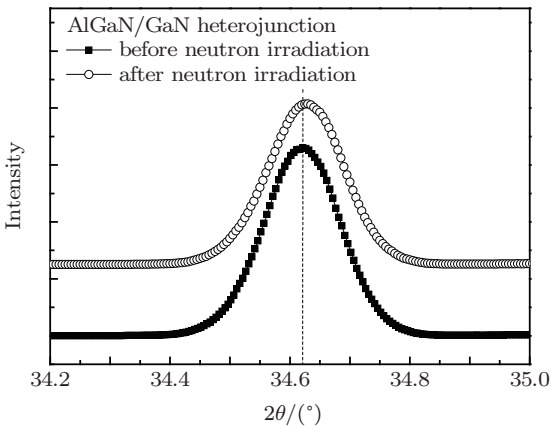


Fig. 7. XRD spectra of AlGaN/GaN heterojunction before and after neutron irradiation.

It has been previously observed that the particle radiation primarily displaces gallium and nitrogen atoms from the crystal lattices and creates charged defect centers. Defect centers degrade the carrier mobility through Coulomb interactions and degrade the carrier concentration in the 2DEG through charge compensation and carrier removal. Therefore, we concentrate on the point defects introduced by neutron irradiation. Earlier research indicated that the A_1(LO) peak position in the Raman scattering spectra clearly shifted toward the low-frequency side and FWHM of PL spectra became larger after neutron irradiation. From the analysis of the Raman and PL spectra, it has been found that the point defects in GaN were induced by irradiation.[9] Many researches concentrated on the defect-related energy levels caused by neutron irradiation.[10–13] Neutron irradiation introduces electron traps with the activation energy of 0.35 and 0.45 eV in the AlGaN barrier and hole traps with the activation energy of 0.26, 0.6, and 1 eV either in the GaN buffer or in the AlGaN barrier.[10] Because the $V_{\rm th}$ shift is positive, we comment on the physical nature of the acceptor-like traps introduced by neutron radiation. One of the most reasonable candidates is the Ga vacancy ($V_{\rm Ga}$), which has relatively low formation energy in n-type GaN when Fermi level is close to the conduction band. Being an acceptor-like defect, $V_{\rm Ga}$ acts as a compensation center. The Ga vacancies are mobile in a wide range of temperature typically used during growth or thermal annealing. It is likely that they migrate and form complexes with more stable defects.[14] We think that the $V_{\rm Ga}$-related defect introduced by neutron irradiation is the main reason for the degradation of the concentration of 2DEG in AlGaN/GaN HEMT devices. After the neutron irradiation, more point defects are generated. As the vacancy concentration increases, the mobility decreases. Therefore, we think that the point defects induced by neutron irradiation are the dominant mechanisms responsible for degradations of performance of 2DEG.

4. Conclusion

In conclusion, AlGaN/GaN HEMTs show a remarkable resistance to neutron–induced degradation with changes of dc and rf parameters. It is clear that neutron irradiation does not affect the material dislocation, however, it does affect the point defects. It is concluded that degradations in carrier density and carrier mobility are the dominant mechanisms responsible for changes in the device-level characteristics.

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