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Early stage degradation related to dislocation evolution in neutron irradiated AlGaN/GaN HEMTs

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ABSTRACT

The early stage degradation of electrical properties in AlGaN/GaN high electron mobility transistors (HEMTs) under fast neutron irradiation is studied. After the 1 MeV neutron irradiation at a low fluence of 1×10^{14} neutrons/cm^2, the reverse leakage current decreases while the output and transfer characteristics remain unchanged, which cannot be explained by the previously reported high-fluence degradation model. By employing temperature-dependent gate leakage current measurements, we show that the dislocation related Poole–Frenkel (PF) emission dominates the gate leakage mechanism before and after irradiation whereas the barrier height for electron emission to conductive dislocation increases after the neutron irradiation. A model with the evolution of dislocation from the V_{Ga}-decorated configuration to the pure configuration is proposed to describe the degradation of AlGaN/GaN HEMTs at the low-fluence early stage neutron irradiation. This model enriches the understanding of the degradation mechanism of neutron irradiated AlGaN/GaN HEMTs.

AlGaN/GaN high electron mobility transistors (HEMTs) are excellent candidates for high voltage, high power, and high frequency applications due to the wide bandgap, high breakdown fields, and strong polarization of the AlGaN/GaN heterostructures.[1] Industrial-grade power amplifiers and aerospace front end modules based on the AlGaN/GaN HEMTs have been widely put into practice.[2,3] It is well known that GaN is more tolerant to radiation than Si and GaAs benefiting from the strong bond strength and higher displacement threshold energy.[4] Therefore, AlGaN/GaN HEMTs own great potential in extreme environments, where the devices are often subjected to the irradiation of electrons, gamma rays, protons, heavy ions, or neutrons. Among the radiation particles, it is found that neutrons exert the most significant effect on the electrical properties of AlGaN/GaN HEMTs.[5] When the energy and fluence of the neutron irradiation exceeds the displacement threshold energy of Ga or N atoms, displacement damage occurs and the device performance undergoes degradations upon the neutron irradiation. Therefore, it is imperative to investigate the electrical behavior on AlGaN/GaN HEMTs in the neutron radiation circumstances.

Previous research studies reported the effect of neutron irradiation on the DC characteristics of AlGaN/GaN HEMTs.[6–11] After neutron irradiation at high fluences, it was widely found that the drain current, threshold voltage (V_{th}), and gate leakage current changed. These changes are attributed to the formation of point defects, which is proposed to modulate the energy band of the AlGaN/GaN heterostructure and change the density or mobility of 2DEG.[9–11] The high fluence is the accumulation of low fluence in time and therefore the low fluence can be regarded as the early stage of high fluence. At low fluences, only the change of gate leakage current was observed while the output and transfer curves remained unchanged after irradiation.[10,11] This cannot be explained within the framework of the point-defect picture for the issue concerning high fluences, in which the conduction band edge position and the properties of 2DEG change. A deep insight into the change of electrical properties of irradiated AlGaN/GaN HEMTs at low fluences has not been well exploited, though it may be of great importance in understanding the early stage degradation of the neutron irradiated AlGaN/GaN HEMTs.

In this work, we investigate the effect of low-fluence neutron irradiation on the electrical properties of AlGaN/GaN HEMTs. The decrease in reverse leakage current with no change of the output and transfer characteristics is observed. Temperature-dependent current–voltage (I–V) measurements are carried out to inspect the gate leakage mechanism before and after irradiation. We find that the dislocation-related Poole–Frenkel emission mechanism dominates before and after irradiation. The barrier height for electron emission from the metal Fermi level to the conductive dislocation states increases, while the conduction band edge position remains unchanged after the low-fluence irradiation. Finally, we propose that the evolution of conductive threading dislocation from the V_{Ga}-decorated configuration to the pure configuration accounts for the decrease in gate leakage current in low-fluence neutron irradiated AlGaN/GaN HEMTs.

The AlGaN/GaN epitaxial structures used in this work were grown on a 6-in. SiC substrate by metal organic chemical vapor deposition (MOCVD). The epilayers starting from the substrate are as follows: an AlN nucleation layer, a 2-μm GaN buffer layer, a 1-nm AlN interlayer, a 22-nm $Al_{0.22}Ga_{0.78}N$ barrier layer, and a 3-nm GaN cap layer. The source and drain Ohmic contacts were obtained by the evaporation and lift-off of Ti/Al/Ni/Au (20/150/50/100 nm) metal stacks, followed by rapid thermal annealing at 850 °C for 30 s in an N_2 atmosphere. Then the isolation was achieved by boron ion implantation. The T-gate Schottky contact was formed by using Ti/Pt/Au (50/50/500 nm) metal stacks. The gate length defined by the electron beam lithography was 80 nm. The gate width was $2 \times 50\ \mu$m. Then Ti/Au (50/500 nm) metals were used to form and thicken the connect pads. The neutron radiation experiments were performed at the Chinese Fast Burst Reactor-II (CFBR-) of Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, which provides a controlled 1 MeV equivalent fast neutron radiation. In this paper, the AlGaN/GaN HEMTs were irradiated with a fluence of 1×10^{14} neutrons/cm^2 at room temperature. The fluence rate is 2×10^9 neutrons/(cm^2· s) and the irradiation time is 5×10^4 s. The devices were measured on-wafer before and after the neutron irradiation by a Keysight B1500A analyzer to acquire the DC characteristics.

The output characteristics of AlGaN/GaN HEMTs are obtained before and after the neutron irradiation. During the measurements, the gate voltage (V_{gs}) ranges from −6 V to −0.5 V in steps of 0.5 V. As shown in Fig. 1(a), the drain current almost remains the same after the neutron irradiation. The transconductance and the transfer curve also remain unchanged within the error range [Fig. 1(b)]. These results indicate that the mobility and concentration of 2DEG are not affected in the process of low-fluence neutron irradiation, which is consistent with the reported literature studies.[12,13] It should be noted that we have checked the effect of low-fluence neutron irradiation on the output and transfer characteristics in 10 devices. All devices exhibit the same phenomenon after irradiation.

Then we investigate the effect of neutron irradiation on the gate current of AlGaN/GaN HEMTs. The gate current was measured with both the drain and source electrodes grounded at room temperature. After irradiation at a fluence of 1×10^{14} neutrons/cm^2, the forward gate current exhibits negligible change while the reverse gate leakage current decreases in irradiated devices. Therefore, we focus on the effect of neutron irradiation on the reverse gate leakage current. One typical comparison result is shown in Fig. 2. The reduction shows that the gate leakage current is more sensitive to the neutron radiation than the drain current, i.e., the 2DEG channel current. This individual reduction of gate leakage under low-influence neutron irradiation in our work is consistent with the previous work.[10] We checked the leakage current after 1 month and the reduction of gate leakage current cannot recover, which excludes the radiation induced trapping effect.

Obviously, the degradation mechanism for the electrical properties of irradiated AlGaN/GaN HEMTs at low fluences is different to

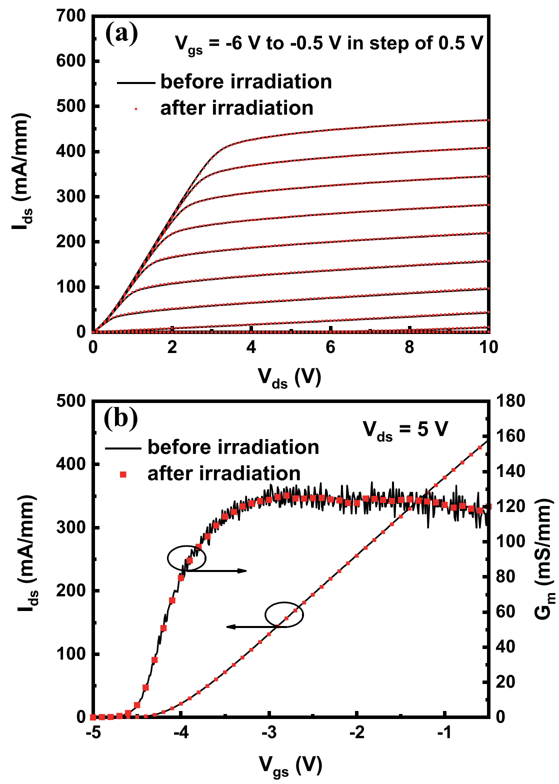

FIG. 1. (a) Output and (b) transfer characteristics of AlGaN/GaN HEMTs before and after irradiation.

the previous framework of the point-defect picture concerning high fluences, in which the conduction band edge position and the properties of 2DEG change. Thus, we investigate the irradiation effect on the individual leakage behavior of AlGaN/GaN HEMTs. The electrical behavior of gate Schottky contacts under the reverse bias is commonly related to two models: the Fowler–Nordheim (FN) tunneling model,[14,15] and the Poole–Frenkel (PF) emission model.[16–18] The FN current is nearly independent of temperature and dominates at very low temperatures (<150 K). The PF current is the electron emission via a conductive dislocation, which exhibits a strong relationship with both the temperature and voltage. In order to investigate the dominant mechanism of gate leakage current, we conducted temperature-

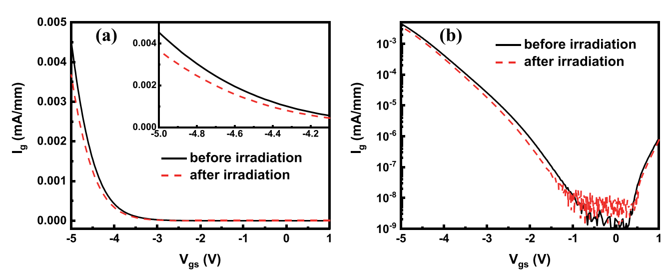

FIG. 2. Gate leakage current of AlGaN/GaN HEMTs before and after irradiation in (a) linear scale and (b) semi-log scale.

dependent I–V measurements of gate leakage current before and after irradiation over a temperature range from 318 K to 478 K. As shown in Fig. 3(a), the gate leakage current before low-fluence neutron irradiation is significantly dependent on both the temperature and voltage, indicating that the PF current is the dominant leakage current component. The similar results are obtained after irradiation, which means the leakage mechanism does not change during the irradiation. The PF current is given by[16]

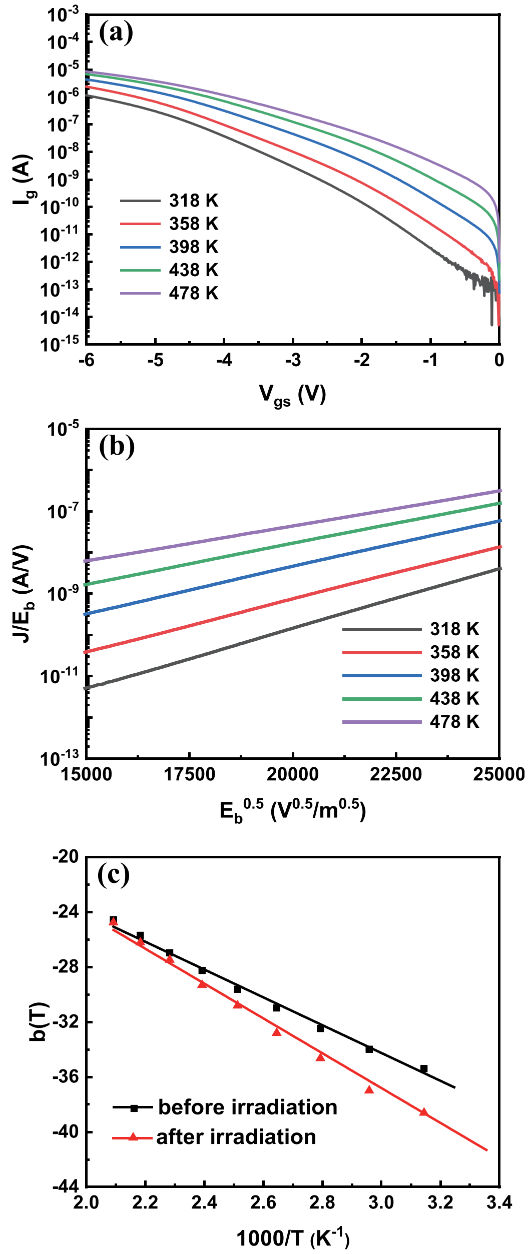

FIG. 3. (a) Temperature-dependent I–V plot of AlGaN/GaN HEMTs. (b) PF emission plot of AlGaN/GaN HEMTs. (c) Plot of $b(T)$ vs $1000/T$ before and after irradiation.

$$J_{PF} = CE_b \exp\left[-\frac{q\left(\phi_t - \sqrt{qE_b/\pi\varepsilon_0\varepsilon_s}\right)}{kT}\right], \tag{1}$$

where C is a constant, E_b is the electric field in the AlGaN barrier under the Schottky metal, ϕ_t is the barrier height for electron emission from the metal Fermi level to the conductive dislocation, ε_0 is the permittivity of free space, ε_s is the high-frequency relative dielectric permittivity, k is the Boltzmann's constant, and T is the temperature. This equation can be deduced as follows:

$$\log\left(\frac{J_{PF}}{E_b}\right) = \frac{q}{kT}\sqrt{\frac{qE_b}{\pi\varepsilon_0\varepsilon_s}} - \frac{q\phi_t}{kT} + \log(C)$$
$$= \frac{q}{kT}\sqrt{\frac{q}{\pi\varepsilon_0\varepsilon_s}}\sqrt{E_b} + b(T), \tag{2}$$

where

$$b(T) = -\frac{q\phi_t}{kT} + \log(C). \tag{3}$$

According to Eq. (2), in the PF model, the term of $\log(J_{PF}/E_b)$ has a linear relationship with $\sqrt{E_b}$. As shown in Fig. 3(b), the linear dependence of measured $\log(J_{PF}/E_b)$ on $\sqrt{E_b}$ further proves the dominant mechanism of PF emission before the neutron irradiation. A similar result after irradiation also proves that the mechanism does not change. The curves $b(T)$ vs $1/T$ before and after irradiation are plotted in Fig. 3(c). With the slope of these curves, the barrier height ϕ_t before and after irradiation is extracted as 0.87 V and 1.09 V, respectively. As mentioned above, ϕ_t is the activation energy from the metal Fermi level into a continuum of states associated with a conductive dislocation. Thus, it is highly expected that the increment of ϕ_t originates from the change of the dislocation state energy caused by the neutron irradiation.

In AlGaN/GaN heterostructures, the density of threading dislocations is as high as 10^7–10^{11} cm^{-2}.[19] The dominant edge dislocations and mixed dislocations create continuum defect states under the conduction band minimum (CBM) of the GaN and AlGaN alloys.[20–23] Because threading dislocations in semiconductors are electronically active, they can interact with other point defects.[24] The interaction lowers the formation energies and changes the positions of defect states of dislocations, due to the electron transfer between dislocations and point defects.[24] For AlGaN alloys, the dominant vacancies of group III atoms (V_{III}) would decorate the threading dislocations and lower their formation energies.[23] V_{III}-decoration turns the deep level states of pure threading dislocations to deeper states away from the CBM [Fig. 4(a)].[25] The neutron irradiation would induce the

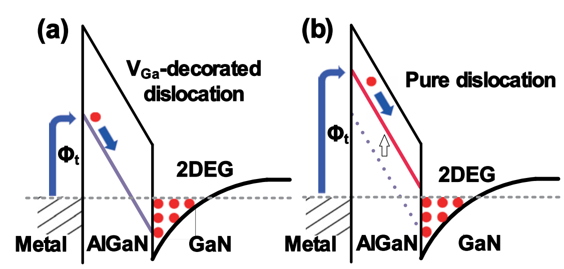

FIG. 4. Band diagrams of AlGaN/GaN heterostructures at equilibrium (a) before and (b) after irradiation.

displacement damage, in which neutrons and the host atoms scatter and generate the point defect.[26,27] When irradiation occurs, neutrons first cause displacement damage in the AlGaN barrier. The displacement energy of N atoms is four times larger than that of Ga atoms by neutron irradiation,[11] and thus, Ga atoms are more easily scattered. At the early stage, the Ga atoms would interact with the V_{Ga}-decorated dislocations and turn them into pure dislocations. Because the energy of the pure dislocations is higher than the energy of V_{III}-decorated dislocations under the CBM,[24,25] the neutron irradiation increases the barrier height of electron emission from the metal Fermi level into a continuum dislocation state [Fig. 4(b)]. The evolution of dislocation does not generate excessive acceptors or donors in the AlGaN barrier. Therefore, the band structure of the AlGaN/GaN heterostructure does not change during the low-fluence neutron irradiation.

It is important to note that the above physical mechanism not only depicts the low-fluence case, but can also explain the degradation of AlGaN/GaN HEMTs at the early stage neutron irradiation with a high fluence. The high fluence is the accumulation of low fluence in time. As the fluence of neutrons progressively increases from low fluence to high fluence, the passivation of Ga atoms on V_{Ga}-decorated dislocations saturates and the scattered Ga atoms diffuse out. The excessive creation of V_{Ga} or other point defects in the perfect region of the AlGaN barrier would modulate the energy band of the AlGaN/GaN heterostructure, change the gate leakage current mechanism, and shift the V_{th}, which has been well explored in AlGaN/GaN HEMTs irradiated by high-fluence neutrons.[9,10] Our work bridges the two distinct degradation regions when the neutron fluence increases.

In conclusion, the effect of low-fluence fast neutron irradiation on the electrical properties of AlGaN/GaN HEMTs has been investigated. After the 1 MeV neutron irradiation at the fluence of 1×10^{14} neutrons/cm^2, the output and transfer characteristics basically remained at the same level, indicating that neither the mobility nor the concentration of 2DEG degraded. The analysis from the temperature-dependent gate leakage current measurements reveals that the dominant leakage current mechanism remains as the dislocation-related PF model before and after irradiation. The barrier height of electron emission to the conductive dislocation states in the AlGaN barrier increases after irradiation. At last, we propose that the evolution of conductive dislocation from the V_{Ga}-decorated configuration to the pure configuration by capturing the Ga atoms scattered by neutron interaction accounts for the degradation in AlGaN/GaN HEMTs at early stage neutron irradiation. This model depicts the early stage degradation of neutron irradiated AlGaN/GaN HEMTs and thus connects the degradation mechanism under low fluences and high fluences, which enriches the understanding of the degradation mechanism of neutron irradiated AlGaN/GaN HEMTs.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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