Effects of Gd_2O_3 Gate Dielectric on Proton-Irradiated AlGaN/GaN HEMTs

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***Abstract*—AlGaN/GaN HEMTs and MOS-HEMTs using Gd_2O_3 as gate dielectric were irradiated with 2 MeV protons up to fluence of 1×10^{15} cm^{-2}. Results showed that proton irradiation causes a strong degradation in the Schottky gate devices, featured by more than three orders of magnitude increase in reverse leakage current, a 30% decrease in maximum drain current and same percentage of increase in ON-resistance, respectively. Scanning transmission electron microscopy showed that radiation induced a diffusion of Ni into Au in the gate and void formation, degrading the transistors characteristics. The Gd_2O_3 gate dielectric layer prevented this diffusion and void formation. MOS-HEMTs with Gd_2O_3 gate dielectric show 50% less decrease of performance under proton irradiation than Schottky gate HEMTs (conventional HEMTs). The trapping effects of Gd_2O_3 gate layer before and after irradiation are also discussed.**

***Index Terms*—AlGaN/GaN, HEMTs, MOS-HEMTs, proton irradiation.**

I. INTRODUCTION

GALLIUM nitride based high electron mobility transistors (HEMTs) are key devices for high power and high frequency applications [1]–[3]. Also they have shown a prospective potential for aerospace application due to good tolerance towards harsh temperature and irradiation environment [4]–[7]. However, high gate leakage current is still one of the most relevant problems which needs to be solved to improve the performance and reliability of the devices [8]. In this regard, metal-oxide-semiconductor HEMTs (MOS-HEMTs) with a thin dielectric layer between gate and barrier layer on AlGaN/GaN heterostructure are being studied to solve the problem, such as SiO_2 [9], Al_2O_3 [10], HfO_2 [10], Gd_2O_3 [11], [12] and so on.

Studies of irradiation effects on AlGaN/GaN based HEMTs and MOS-HEMTs (using Al_2O_3 [13], NbAlO [14], SiO_2 [15], MgO or Sc_2O_3 [16]) have been explored using different energies and fluences, experimentally [6, 7] and by simulation [21]–[23]. For instance, the Al_2O_3/AlGaN/GaN MOS-HEMTs showed over 50% decrease in maximum drain current after 5×10^{15} cm^{-2} fluence irradiation with 5 MeV protons [13]. NbAlO AlGaN/GaN Metal Insulator Semiconductor (MIS) HEMTs with Si_3N_4 passivation showed a decrease in DC-IV properties after 3 MeV proton irradiation with 1×10^{15} cm^{-2} fluence [14]. However, the degradation mechanisms of the devices after irradiation are still unclear in many cases.

In this work, we investigated the effects of proton irradiation on AlGaN/GaN devices and MOS devices with Gd_2O_3 as the gate dielectric layer. The thin layer of Gd_2O_3 was deposited using a novel low-damage technique based on high pressure sputtering [12]. For comparison purposes Schottky gate diodes and HEMTs were fabricated simultaneously with the MOS-devices on the same piece of wafer. The proton energy was designed to be 2 MeV, and the fluence was 1×10^{13} and 1×10^{15} cm^{-2}, respectively. The experimental details and the irradiation tests are described in Section II. The results of the electrical characterization of the devices before and after irradiation are shown in Section III, leaving the discussion of the performances in HEMT and MOS-HEMT devices at the end of that section.

II. EXPERIMENTAL DETAILS

The devices were fabricated on AlGaN/GaN heterostructures grown on (111) silicon wafer with a GaN cap grown by metal-organic chemical vapor deposition. The Al content and the thickness of the AlGaN layer is 32% and 22.5 nm, respectively. The GaN layer is unintentionally doped, with a thickness of 0.1 μm. The GaN cap is 2 nm. Several groups of HEMTs and diodes (both Schottky gate and MOS-based) were processed simultaneously on the wafer by the following procedure.

A 20 nm Ti/120 nm Al/40 nm Ni/50 nm Au metal stack, used

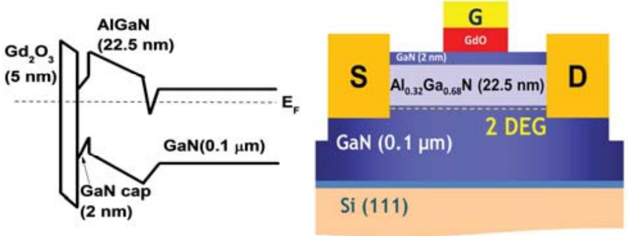

Fig. 1. (a) Sketch of energy band diagram and (b) Schematic cross-section of Gd_2O_3/AlGaN/GaN based MOS-HEMTs.

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as ohmic contact, was e-beam evaporated and then rapid-annealed at 850ºC for 30 s in a two-step ramp in N_2 ambient. Afterwards, device isolation trenches of about 100 nm deep were fabricated by inductively coupled plasma etching using Cl_2/Ar based processes. The contact resistance (R_c) of the ohmic contacts was 0.86 Ω·mm and the sheet resistance (R_{sheet}) of the 2-dimensional electron gas was 263 Ω/□, as calculated by means of the transmission line method (TLM). The sheet carrier density (n_s) and the electron mobility (μ) of the devices calculated from Hall measurements were 8×10^{12} cm^{-2} and 1100 cm/V·s.

After the previous steps, one half piece of the sample was covered by photoresist. The other half was gate patterned using standard photolithography. A thin layer of Gd_2O_3 was deposited on the sample using high pressure sputtering method at room temperature, following the same procedure described in [13]. The layer thickness and root mean square (rms) roughness of the deposited Gd_2O_3 layer evaluated using atomic force microscope, were 4.2 ± 0.3 nm and 2.1 nm, respectively.

Then the metallization of the gate contact Ni (20 nm)/ Au (200 nm) and lift-off were performed. Afterwards, the other half piece of sample was gate patterned with photolithography and followed by the same gate contact metallization, while the half piece with finished MOS gate structures was protected with photoresist. The gates of the HEMT devices are 1.2 μm in length and 50 μm in width, and the distance between source and drain is 5 μm. The diodes have square shape with a side length of 100 μm. In order to study the effects of the gate dielectric on the device stability after irradiation, Gd_2O_3 was deposited only under the gate without any passivation.

The samples were characterized electrically, then irradiated with 2 MeV protons produced with a 5 MV Cockroft-Walton tandem accelerator (1×10^{13}, 1×10^{15} cm^{-2}), under air condition, with all contacts open. Prior to the irradiation, the homogeneity of the collimated beam was measured with a quartz reference sample. According to TRIM simulations [24], the projected range of the protons is 24.6 μm, with a straggle of 0.9 μm. After the irradiation, the same electrical measurements were carried out on the devices.

The measurement procedures used in the study include TLM and Hall measurements; current-voltage (I-V) and capacitance-voltage-frequency (C-V-f) characterizations, DC I-V and transfer characterization of the HEMTs and MOS-HEMTs. In addition, scanning transmission electron microscopy (STEM) and energy-dispersive X-ray spectroscopy (EDS) were performed.

III. RESULTS AND DISCUSSION

The change in the DC parameters of the conventional HEMTs and MOS-HEMTs as a function of the fluence (1×10^{13}, 1×10^{15} cm^{-2}) is shown in Fig. 2. The changes observed after 1×10^{13} cm^{-2} proton irradiation are relatively small (-13% in $I_{D,max}$, +10% in R_{ON} and -10% in $g_{m,max}$), for both conventional and MOS-HEMTs, in good agreement with the literature [25]. On the contrary, after 1×10^{15} cm^{-2} irradiation, conventional HEMTs showed a severe change and significant differences with respect to MOS-HEMTs. Therefore, further analysis will be focus on the effects of 1×10^{15} cm^{-2} proton irradiation for both conventional and MOS-based devices.

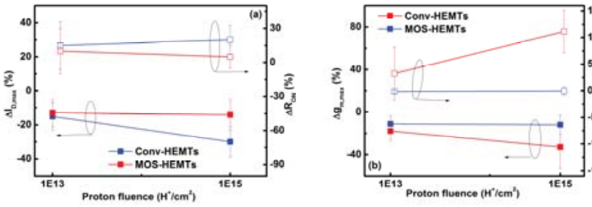

Fig. 2. Change in the (a) $I_{D,max}$, R_{ON}, and (b) $g_{m,max}$, $I_{G,\ off}$ as a function of the proton fluence for both conventional and MOS-HEMTs.

For the diodes, I-V characteristics of the AlGaN/GaN Schottky and Gd_2O_3 based MOS-diodes, before and after proton irradiation, are shown in Fig. 3(a). Results show that after the irradiation, the reverse gate current density (J_{rev}) increased in both Schottky diodes and MOS-diodes. However, J_{rev} of the MOS-diodes was 10^3 lower than that of the Schottky diodes after irradiation. Similar increases in J_{rev} have been observed in conventional HEMTs after irradiation with proton of 5 MeV and 2×10^{14} cm^{-2} [26].

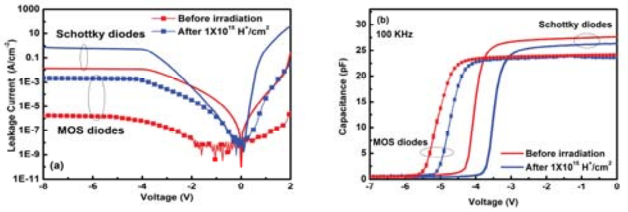

Fig. 3. (a) Current-Voltage and (b) Capacitance-Voltage characteristic of the Schottky and MOS diodes before and after irradiation.

The capacitance-voltage characteristics of the Schottky and MOS diodes are shown in Fig. 3(b). Both Schottky and MOS diodes showed a positive shift of threshold voltage (V_{TH}) after irradiation: from -4.2 V to -3.7 V in Schottky diodes, and from -5.5 V to -5.0 V in MOS-diodes. This shift could be related to the creation of acceptor type defects in the Gd_2O_3/heterostructure interface or in the AlGaN/GaN channel. These defects are, most likely, N vacancies [21] and Ga-N divacancies [27]–[29] and Ga vacancies [30]. The n_s and μ measured decreased after irradiation for all the devices. However, the decrease of n_s and μ in the MOS-HEMTs is smaller than that of the conventional HEMTs.

DC I-V characteristics of the conventional and MOS-HEMTs before and after proton irradiation are shown in Fig. 4(a). For the conventional HEMTs, the maximum drain current ($I_{D,max}$) and ON-resistance (R_{ON}) decreased and increased by 30%, respectively, after irradiation. On the contrary, for the

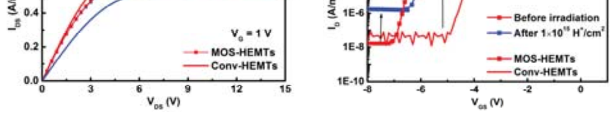

Fig. 4. (a) I_D-V_{DS} properties at V_G = 1 V and (b) I_D-V_{GS} properties at V_{DS} = 9.9 V of the AlGaN/GaN HEMTs and Gd_2O_3-AlGaN/GaN MOS-HEMTs before and after irradiation

MOS-HEMTs, $I_{D,max}$ decreased by 15% and R_{ON} did not change significantly, after irradiation.

The cause of $I_{D,max}$ reduction and R_{ON} increase is related to the decrease of sheet carrier density and electron mobility in the channel [25, 31, 32]. During transconductance measurements, the Schottky gate HEMTs showed a 29% decrease of the peak transconductance ($g_{m,max}$), and the MOS-HEMTs showed only a 10% reduction. Positive shift in the V_{TH} was observed in the conventional and MOS-HEMT, in good agreement to those in the Schottky- and MOS-diodes, with a similar tendency as MIS-HEMTs using NbAlO after irradiation [14].

Fig.4(b) showed that the off state drain current ($I_{D,OFF}$) increased after irradiation in both kinds of HEMTs, but the increase in the MOS gate HEMTs is about two orders of magnitude lower, than that of the Schottky gate HEMTs. Therefore, the on/off current ratio in the MOSHEMTs is 10^2 higher than in conventional HEMTs, which makes Gd_2O_3 dielectric layer also very attractive for switching applications under proton irradiation environment.

In order to analyze the trapping effects in the devices, gate and drain lag ratios were extracted from double pulsed measurements before and after irradiation. The lag ratio is defined as I_D^{pulsed}/I_D^{ref} at drain bias of 4.5 V and gate bias of 1 V for the devices. Fig. 5 shows that the gate and drain lag ratio decreased over 13% in conventional HEMTs, and about 6% in MOS-HEMTs after irradiation, proving the existence of irradiation caused defects in the devices. However, the MOS-HEMTs showed 28% higher gate lag ratio and 18% higher drain lag ratio than the conventional HEMTs, showing that the Gd_2O_3 dielectric under the gate is able to diminish the effects of irradiation on the heterostructure. It works as an irradiation-hardening mechanism, partially protecting the HEMTs from crushing down during proton irradiation.

In order to gain further insight on the degradation mechanisms of the devices after irradiation, STEM measurements in the gate region before and after irradiation were compared between Schottky gate and MOS HEMTs. In the case of conventional HEMTs, a tilt of the gate edge and voids under the gate were observed after irradiation, as shown in Fig. 6(c), in contrast to the device before irradiation in Fig. 6(a). The origin of these voids is likely the diffusion of Ni into Au in the Ni/Au gate metal via defect migration mechanisms such as vacancy exchange or Frenkel pair formation/recombination. In the MOS-HEMTs, neither the gate edge tilt nor the irradiation induced Ni voids were observed (Fig. 6(d)), showing that the use of the Gd_2O_3 gate dielectric is effective to mitigate the detrimental damage of the gate stack in the GaN based HEMTs.

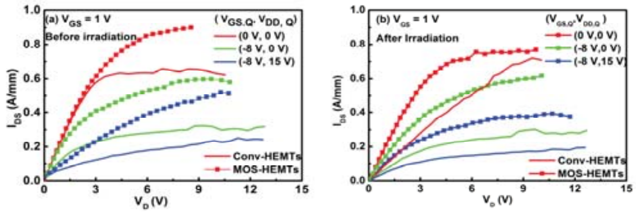

Fig. 5. Pulsed I-V curves of the AlGaN/GaN HEMTs and Gd_2O_3-AlGaN/GaN MOS-HEMTs (a) before and (b) after irradiation.

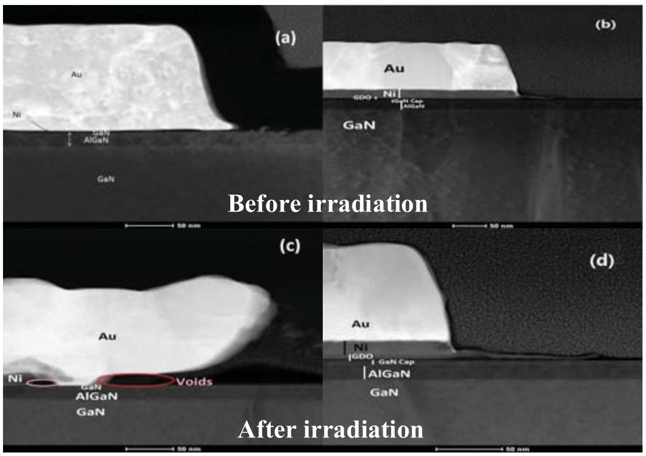

Fig. 6. STEM cross-section images before and after irradiation of the Ni/Au gates on the (a)(c) conventional HEMTs and (b)(d) Gd_2O_3-AlGaN/GaN MOS-HEMTs.

Devices characterization were carried out after several months room temperature annealing, 15% $I_{D,max}$ decrease were observed in the conventional HEMTs, due to the physical damage on the gate edge, while no change was observed in the MOS-HEMTs.

Defects are induced through ion-electron collision to the devices during the proton irradiation. On one hand, the collisions cause electrons generation and recombination in the heterostructure, producing vacancies and defects in the device. These vacancies and defects would lead to sheet carrier density and carrier mobility decrease, and result in a positive shift in V_{TH} and a decrease in current density [26, 29, 33]. On the other hand, during the collision of protons and electrons, heat would be generated in the heterostructure, which would be partial cause of the diffusion between the metals [5].

IV. CONCLUSIONS

In conclusion, proton-induced radiation effects, with 2 MeV energy and 1×10^{15} cm^{-2} fluence, in AlGaN/GaN conv-HEMTs and Gd_2O_3-AlGaN/GaN MOS-HEMTs are reported. Results show that Gd_2O_3 gate dielectric eases the electrical degradation by proton irradiation in both DC and pulsed characteristics respect to the Schottky-gate devices. Moreover, it is proved that Gd_2O_3 layer under the gate metallization helps to avoid the tilt of the gate edge and voids under the gate, which is observed in the conventional AlGaN/GaN HEMTs after proton irradiation. Therefore, these results show that the use of the Gd_2O_3 gate dielectric is effective to mitigate the damage to the gate stack in the GaN based HEMTs, and open the possibility of developing Gd_2O_3 based MOS-HEMT to enhance the device robustness for high radiative environment applications.

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