Degradation Characteristics of AlGaN/GaN MOS-Heterostructure FETs by Alpha-Particle Irradiation

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Extreme environment electronics is a key technology to further excavate natural resources on the earth and explore the space environment successfully. In this system, semiconductor devices are important elements because robust reliability with long life time should be guaranteed. Radiation-hardness is one of the material requirements imposed by the mission being carried out in the extreme environment such as the space and the nuclear plant. Wide bandgap semiconductors such as GaN and SiC are recently introduced as a strong candidate for harsh environment application. With the recent advancement of GaN epitaxial and process technology, AlGaN/GaN HFETs demonstrated rapid performance improvement in both high frequency and high-power applications and its excellent material properties deliver the potential to endure extreme environments such as high temperature, high radiation, and etc.1–4

The cosmic-ray of the space environment contains diverse radiation sources such as protons, alpha-particles, electrons, neutrons, and heavy ions at a wide range of energy. Although protons are the primary source of Van Allen radiation belt where majority of space facilities and spaceships are, alpha-particles which generate the primary source of Van Allen radiation belt where majority of cosmic-ray.5-6 Therefore, the response of AlGaN/GaN MOS-HFETs with alpha-particle irradiation is considerably important for the reliability of space electronics. Radiation response to proton irradiation of GaN-based devices are widely investigated and demonstrated.3-9 However, studies of alpha-particle irradiation on AlGaN/GaN HFETs are seldom reported.10

In this work, alpha-particle irradiations were performed on normally-on AlGaN/GaN MOS-HFETs and schottky HFETs fabricated on GaN-on-Si substrate. Then, we compared the results observed from both devices and investigated the mechanism of degradation. The irradiated devices showed fluence-dependence of device parameters such as Vth shift and on-current reduction.

Experimental

AlGaN/GaN MOS-HFETs and AlGaN/GaN schottky HFETs were simultaneously fabricated on commercially-available GaN-on-Si wafer. Fig. 1 shows the schematic cross-sectional view of AlGaN/GaN MOS-HFETs and AlGaN/GaN schottky HFETs have no insulator under the gate. The epitaxial structure consisted of a 3.9 μm C-doped GaN buffer layer on a p-type Si (111) substrate, a 400 nm undoped GaN layer, a 20 nm undoped Al0.23Ga0.77N barrier, and a 4 nm undoped GaN capping layer. The gate-to-drain distance, gate length, and gate-to-source distance were 15 μm, 2 μm, and 3 μm, respectively. The width of device is 100 μm.

The device fabrication started with ohmic contact formation. In order to reduce the contact resistance, a recessed contact region was formed by using inductively coupled plasma ion etching (ICP-RIE) with Cl2/BCl3 plasma. Then, a Ti/Al/Ni/Au (=20/120/25/50 nm) metal stack was deposited by electron beam evaporation and alloyed by rapid thermal annealing (RTA) at 830 °C for 30 s. After ohmic contact process, the active regions were defined by mesa structure using Cl2/BCl3-based ICP-RIE. A 20 nm SiO2 layer was deposited as the gate insulator and passivation layer by using plasma-enhanced chemical vapor deposition (PECVD) and annealed by RTA at 400 °C for 10 min in O2 ambient. Schottky gate contact region was etched through gate oxide by CF3/O2-based ICP-RIE. A Ni/Au (=20/200 nm) metal stack was evaporated for gate and pad electrodes simultaneously.

Alpha-particle irradiations were performed at the Korea Institute of Radiological and Medical Sciences using a MC-50 cyclotron.11 Alpha-particle irradiation energy can be modified from 29 MeV to 18 MeV via passing through 0.2 mm aluminum degrader. The devices were irradiated at a room temperature under low vacuum atmosphere. Samples were exposed to fluences of 1013, 1014, and 1015 cm−2 with ion current of 50 nA. No electrical connections were made to the devices during irradiation. Post-irradiation analysis was performed after 1 day for safety measure.

Figure 1. The schematic cross-sectional view of fabricated AlGaN/GaN MOS-HFETs on Si substrate.

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Results and Discussion

DC I-V characteristics were measured before and after irradiation using Agilent 4155A parameter analyzer in order to investigate the alpha-particle irradiation effect on GaN HFETs. The output and the transfer characteristics of AlGaN/GaN MOS-HFETs and AlGaN/GaN schottky HFETs are shown in Figs. 2 and 3. No significant change of device characteristics was observed at alpha-particle fluence of $10^{13}$ cm$^{-2}$. As the fluence increases, the irradiated devices showed significant changes in device characteristics.

After alpha-particle irradiation over $10^{13}$ cm$^{-2}$ of total dose, the change of $R_{on}$ and drain current were observed in the output characteristics. In AlGaN/GaN MOS-HFETs, specific $R_{on}$ was degraded from 2.77 to 6.77 m$\Omega$·cm$^2$ and on-current was reduced by 64.6% as the alpha-particle doses amounted to $10^{15}$ cm$^{-2}$. The maximum transconductance ($g_{m,max}$) was also degraded from 35.4 to 14.8 mS/mm in the linear region (at the $V_D$ of 1 V). In AlGaN/GaN schottky HFETs, specific $R_{on}$ was degraded from 2.56 to 5.93 m$\Omega$·cm$^2$ and on-current was reduced by 60.3% as the alpha-particle doses amounted to $10^{15}$ cm$^{-2}$. The $g_{m,max}$ was also degraded from 64.2 to 27.8 mS/mm. As shown in transfer characteristics, the $V_{th}$ was also shifted to the positive direction. Fig. 4 presents the clear dependence of the $V_{th}$ on alpha-particle fluence indicating that observed changes resulted from the damage induced by alpha particle irradiation.

We analyzed the results obtained from Transfer Line Measurement (TLM) and Hall measurement patterns to investigate the irradiation effect. TLM patterns were measured to extract contact resistance ($R_C$) and sheet resistance ($R_{sh}$). $R_C$ was increased from 1.13 to 2.56 $\Omega$·mm and $R_{sh}$ was increased from 410 to 1129 $\Omega$/$\square$ at the doses of $10^{15}$ cm$^{-2}$. Similarly, increase of $R_{on}$ from 433 to 1363 $\Omega$/$\square$ was measured from Hall pattern. From Hall pattern measurement, we also confirmed that the mobility was decreased from 1620 to 722 cm$^2$/V·s and sheet charge density was decreased from $8.87 \times 10^{12}$ to $6.34 \times 10^{12}$ cm$^{-2}$. Results of hall pattern measurement were summarized in Fig. 5. TLM patterns, which do not have gate structure, exhibited the reduction of current by 70% after irradiated with $10^{15}$ cm$^{-2}$. This amount of current reduction is very close to that of HFETs by 64.6%. It suggests...
that the main mechanism of current reduction should be displacement damage which aggravates carrier transport property in the active semiconductor region.

The C-V characteristics of MOS-HFETs and schottky HFETs before and after irradiation are shown in Fig. 6. The positive shift of C-V curve was observed as same as that of transfer characteristics. Schottky HFETs, which have no gate insulator, also showed the change of C-V characteristics very similar to MOS-HFETs. Although gate leakage current in Fig. 3 was not increased in either of devices, the slope of transition in C-V characteristics was significantly changed in MOS-HFET.

In order to investigate the effect on the oxide interface by alpha-particle irradiation, interface trap density ($D_{it}$) over the bandgap was extracted using DIFT and shown in Fig. 7. This technique previously proposed for the extraction of the subgap density of states in a-IGZO thin film transistors (TFTs) facilitates $V_{th}$-independent extraction of interface states based on I-V curve. After irradiation, the increase of $D_{it}$ was observed from $8.52 \times 10^{11}$ to $3.07 \times 10^{12} \text{cm}^{-2}\text{eV}^{-1}$ at $E-E_C = -0.23 \text{eV}$. The degradation characteristics of the irradiated devices can be linked to the increase of trap density induced by alpha-particle irradiation. Defects which can act as trap states were released by the penetration of alpha-particles into devices.

Then, the annealing treatment was performed using RTA to confirm the effect of displacement induced by irradiation. Thermal annealing can rearrange dislocated atoms and recover electric properties of degraded devices. Fig. 8 shows recovery characteristics of the irradiated devices at 300°C for 5 min under vacuum environment. The temperature of annealing treatment was limited due to the growth temperature of gate oxide ($\text{SiO}_2$). The degraded parameters were partially recovered and these results demonstrate that displacement induced by alpha-particle irradiation was partially rearranged and the resistance of the irradiated devices was decreased.

**Summary**

In conclusion, we performed alpha-particle irradiation on normally-on AlGaN/GaN MOS-HFETs and schottky HFETs fabricated on the same wafer. Both devices exhibited similar post-irradiation characteristics which include the positive shift of $V_{th}$ and reduction of on-current. Hall pattern measurements indicated carrier transport property of 2DEG channel was degraded. C-V characteristics of irradiated devices also showed significant degradation of oxide interface property. Extracted density of states revealed the increase of interface states density after irradiation. Degraded electrical properties were partially recovered by thermal annealing treatment which...
can help dislodged lattice atoms rearranged. We suggest that observed degradation should be attributed to displacement damage induced by alpha-particle irradiation.

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