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Proton Irradiation Effects on GaN-based devices

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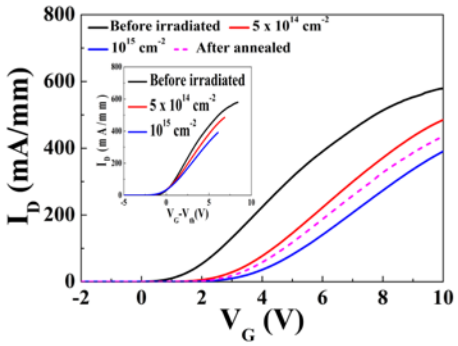
ABSTRACT
Along with the needs for feasibility in the field of space applications, interests in radiation-hardened electronics is growing rapidly. Gallium nitride (GaN)-based devices have been widely researched so far owing to superb radiation resistance. Among them, research on the most abundant protons in low earth orbit (LEO) is essential. In this paper, proton irradiation effects on parameter changes, degradation mechanism, and correlation with reliability of GaN-based devices are summarized.

KEY WORDS
GaN, proton, irradiation, radiation hardness, degradation, space environment.

1. INTRODUCTION
Recently, research on unmanned technologies for development of harsh-environment electronics has been actively conducted. Harsh-environment electronics are important for energy-resource discovery and space exploration. In particular, radiation-resistant electronic components are essential in space environments, where strong cosmic radiation exists. Even in satellites or spacecrafts, equipment and components are exposed to significant radiation and rapid temperature variations.

Gallium nitride (GaN) is attracting attention in the field of space applications owing to its excellent capabilities in harsh environments where temperature, chemicals, and radiation are severe [1]-[3]. In addition, in terms of size reduction, weight reduction, and energy savings, GaN is evaluated as an ideal candidate for use in existing technologies [4], [5]. Electrical systems for space applications are exposed to large amounts of cosmic radiation, such as those from protons, alpha rays, and heavy ions. A low earth orbit (LEO), where satellites and space stations exist, includes high proton fluxes. Therefore, research on the effects of proton irradiation on GaN has been widely reported [6]-[8]. In this paper, the overall proton irradiation effects on GaN-based transistors are introduced.

2. PROTON IRRADIATION EFFECTS ON ELECTRICAL PARAMETERS
Research on the proton irradiation effect of GaN-based transistors using various conditions has been widely reported. Weaver et al. conducted experiments with a beam energy of 2 MeV and fluence of 6×10^{14} cm^{-2}. They presented various characteristics, such as a change in threshold voltage (V_{th}) and decrease in maximum transconductance, and observed proton irradiation effects on various substrates [9]. L. Lv *et al.* observed proton irradiation effects on AlGaN/AlN/GaN structures, and the effects of applied voltage during proton irradiation were reported by J. Chen *et al.* [10], [11].



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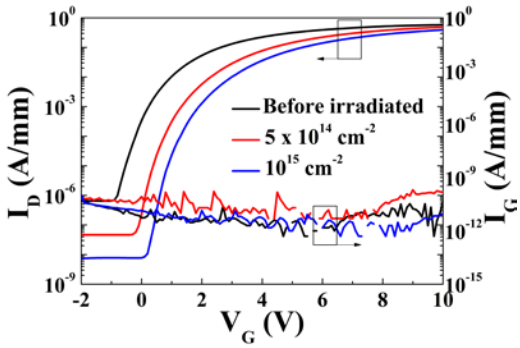

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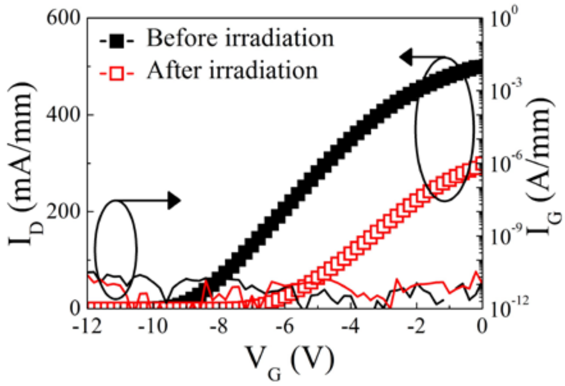
Figure 1. The transfer characteristics of AlGaN/GaN recessed MISHFETs in (a) linear and (b) logarithmic scale before and after 5 MeV proton irradiation and thermal annealing. (insertion in (a)) Replotted transfer characteristics at V_D = 10 V on the x-axis of V_G-V_{th} [17].

It has been reported that the displacement damage produced by proton irradiation within the semiconductor crystal can reduce the electron concentration and mobility by generating defects. Displacement damage is a major source of degradation concerning proton irradiation, in which particles of high energy collide with the atoms that form the lattice, leaving the atoms out of their original position. In this phenomenon, periodic potential displacement occurs for electrons moving inside semiconductors, causing electrical dispersal of electron mobility [12]-[14].

The dependencies of the dose, energy, and gate structure of the proton irradiation effects are summarized in Section 2, and the impact of proton irradiation on reliability is summarized in Section 3. The beam energy and irradiation fluence are sufficiently set to confirm the deterioration of transistors by referring to previously reported studies on proton irradiation effects [15], [16].

A. Fluence dependence

Proton-irradiated AlGaN/GaN-on-Si recessed metal-insulator-semiconductor heterostructure field effect transistors (MISHFETs) with a beam energy of 5 MeV and beam fluences of 5 × 10^{14} and 10^{15} cm^{-2} exhibit an increase in on-resistance and a positive shift of V_{th}. A decrease in both the maximum transconductance ($g_{m,max}$) and off-state drain current ($I_{D,off}$) was also observed.



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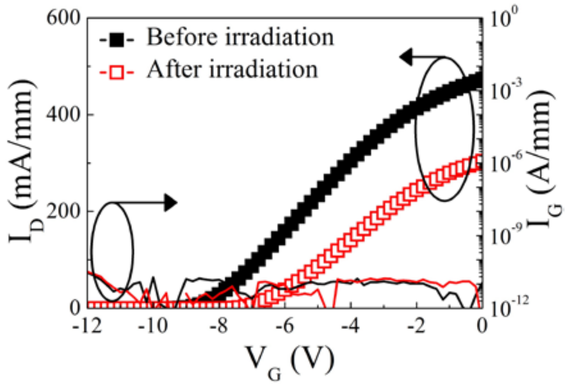

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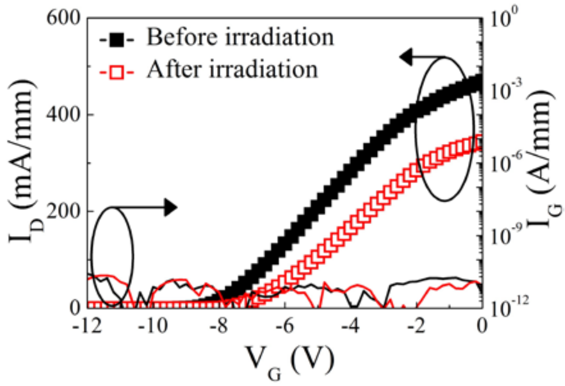


(c)

Figure 2. The transfer characteristics of AlGaN/GaN MISHEMTs before and after (a) 1, (b) 1,5 and (c) 2 MeV proton irradiation. V_D = 10 V [19].

The parameter changes were proportional to the beam fluence changes. Thermal annealing at 300 ºC for 5 min was partially efficient in recovering the transfer characteristics (Figure 1).

A decrease in the two-dimensional electron gas (2-DEG) concentration was confirmed through the sheet-resistance change extracted through transmission line method (TLM) measurements. The current collapse confirmed through pulse measurements and the interface trap change extracted through the differential ideality factor technique (DIFT) identified an increase in the number of trap states generated by displacement damage in the irradiated device [17].

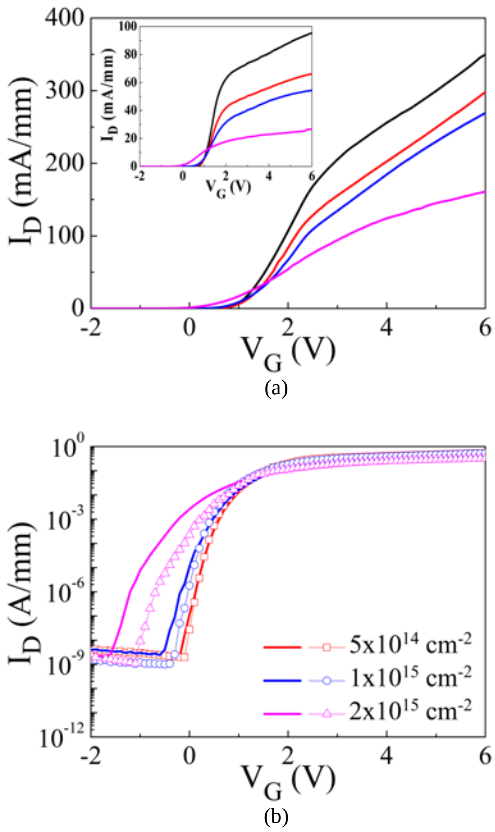


Figure 3. (a) The linear and (b) logarithmic scale of transfer characteristics of normally-off pAlGaN gate AlGaN/GaN HEMTs before and after 5 MeV proton irradiation. V_D = 10 V [22].

B. Energy dependence

Proton irradiation with beam energies of 1, 1.5, and 2 MeV and a beam fluence of 5 × 10^{14} cm^{-2} was performed on AlGaN/GaN MIS high-electron mobility transistors (HEMTs). Parameter-change trends in this case were similar to those with 5 MeV proton irradiation, and the changes were inversely proportional to the beam energy change (Figure 2). Thermal annealing at 400 °C for 10 min was partially efficient in recovering the transfer characteristics.

The stopping and range of factors in matter (SRIM) [18] calculation yields the energy loss in the GaN buffer layer according to the beam energy. The non-ionizing energy loss (NIEL) extracted from SRIM confirms that the lower the beam energy in a beam flux, the higher the displacement damage from proton irradiation [19].

C. Gate structure dependence

GaN-based transistors are advantageous in high channel concentrations without intentional doping owing to their strong polarization effects [20], [21]. However, artificial fabrication processes or process modifications are required to change the normally on (depletion-type) behavior to normally off (enhancement-type) behavior, for ensuring reliability and stability of a power semiconductor device. Previous studies on the proton irradiation effects of GaN-based transistors are limited to Schottky-gate structures; therefore, the results are compared after investigating 5 MeV proton irradiation on normally off pAlGaN-gate GaN HEMTs.

Normally off pAlGaN gate AlGaN/GaN HEMTs irradiated with a beam energy of 5 MeV and beam fluences of 5 × 10^{14}, 10^{15}, and 2 × 10^{15} cm^{-2} exhibited an increase in on-resistance and a decrease in drain current as AlGaN/GaN-on-Si recessed MISHFETs described in Section 2-A. However, the irradiated devices exhibited different trends in subthreshold characteristics. The subthreshold slope was negatively shifted, and the subthreshold swing was sufficiently degraded after proton irradiation (Figure 3). Thermal annealing at 400 °C for 5 min was partially efficient in recovering transfer characteristics, and the recovered quantity was proportional to the irradiation fluence.

Because the normally off pAlGaN gate AlGaN/GaN HEMTs have a structure with only pAlGaN layers added to the conventional Schottky gate AlGaN/GaN HEMTs, Silvaco technology computer-aided design (TCAD) simulation was performed by changing the hole concentration of the pAlGaN layer. Silvaco TCAD simulation indicated that the subthreshold slope shifted toward the negative direction, and the forward current of the gate diode decreased with the hole concentration in the pAlGaN layer. Therefore, it was indirectly confirmed that the hole concentration in the pAlGaN layer decreased as the irradiation fluence increased [22].

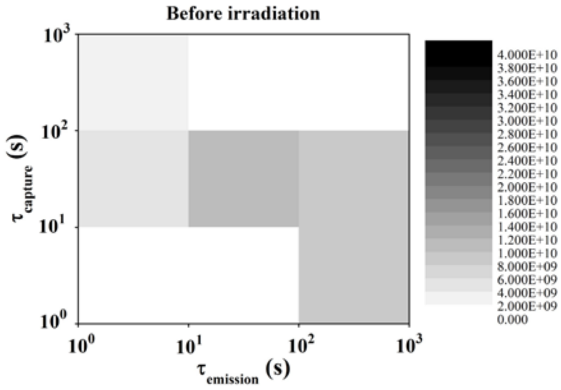
3. PROTON IRRADIATION EFFECTS ON RELIABILITY

Reliability issues must be addressed before commercialization of GaN-based transistors. Several major reliability issues and solutions in GaN-based transistors have been reported. However, limited research has been conducted on the correlation between reliability and radiation for space applications. Therefore, this section summarizes the effects of radiation on the reliability of GaN-based transistors.

A. Charge-trapping instability

The effect of proton irradiation on the charge trapping of AlGaN/GaN recessed MISHFETs during short-term stress tests was observed in the off-state conditions, before and after proton irradiation. The rate of temporary current reduction caused by short-term stress tests deteriorated after proton irradiation, which indicates an increase in charge trapping.

The capture/emission time (CET) map (Figure 4) and the conductance method [23], [24] before and after proton irradiation confirmed that the number of



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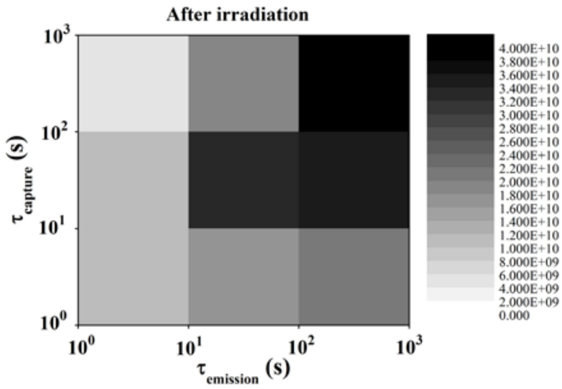

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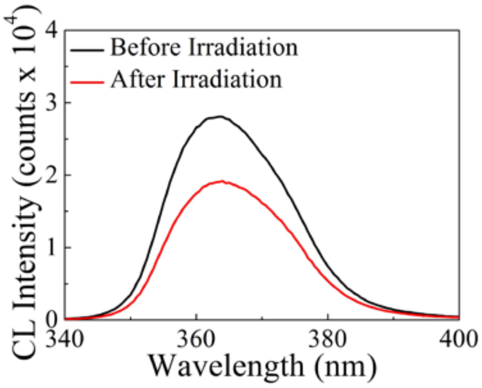
Figure 4. CET maps in AlGaN/GaN recessed MISHFETs (a) before and (b) after 5 MeV proton irradiation [26].



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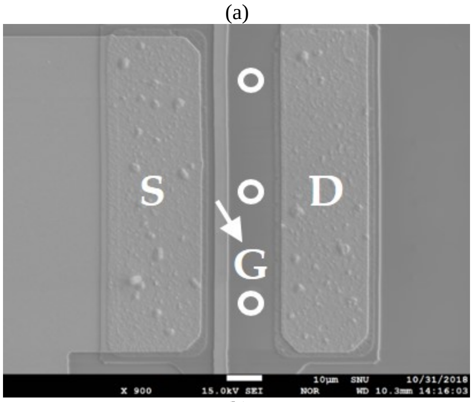

(b)

Figure 5. (a) CL spectra of AlGaN/GaN recessed MISHFETs before and after proton irradiation. (b) SEM image of the analyzed device. [27].

interface states of the gate and access regions was increased, indicating that charge trapping by short-term stress tests was adversely affected.

The drain off-state breakdown voltage (BV) increased after proton irradiation. The proton irradiation effects were indirectly applied by employing negatively charged traps [25] through Silvaco TCAD simulation, and the BV was presumed to increase as the electric field distribution on the gate edge of the drain side decreased after proton irradiation [26].

B. Time-dependent dielectric breakdown (TDDB)

Time-zero breakdown (TZB) and TDDB characteristics were measured before and after proton irradiation to investigate the effects of proton irradiation on the gate reliability of AlGaN/GaN recessed MISHFETs. Although the increase in number of trap states in the gate region was identified using the CET map and cathodoluminescence (CL) analysis (Figure 5), TZB and TDDB showed negligible changes after proton irradiation.

To analyze the origin of negligible changes in TZB and TDDB results before and after proton irradiation, negatively charged traps, calculated from SRIM, were applied to Silvaco TCAD to align transfer characteristics before and after proton irradiation. Simulation results reveal that the vertical field distribution of the identified gate region shows a significant reduction in the vertical field of the gate region after proton irradiation. Therefore, it is estimated that the trap state degradation of the gate region was offset by the reduction of the vertical field of the gate region, resulting in negligible changes in TZB and TDDB [27].

6. CONCLUSION

Research results have been compiled to investigate the proton irradiation effects on GaN-based transistors, a potential candidate for use in space applications. GaN has materially superior radiation-hardened properties; however, reliability and stability issues must be addressed before its practical use in space. Experiments should be continuously conducted to improve the radiation characteristics of GaN-based transistors, and further research is essential to identify more specific and tangible origins.

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