Analysis of Radiation Resistance in GaN HEMT

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Irradiation effects of proton and Ni ions on a gallium nitride high electron mobility transistor (GaN HEMT) were investigated. The device characteristics did not degrade until 1 × 10^{13} protons/cm^2 for 3 MeV proton irradiation. The devices irradiated with high radiance of Ni ions had no increase in leakage current or electric field intensity, indicating there was no critical damage to the devices. These results demonstrate the device has a high radiation tolerance for space application.

1. Introduction

GaN HEMTs are suitable for constituting high-efficiency, high frequency, and high-power devices due to their high carrier mobility and high breakdown voltage. To obtain the advantage of high efficiency, lightweight and high reliability properties, GaN HEMTs are expected to be applied to solid-state power amplifiers (SSPAs) to be mounted on satellites (1).

In space environments, devices mounted on satellites are exposed to space radiation consisting of high-energy electrons, protons, and heavy ions due to supernova explosions and solar activity, as well as X-rays and gamma rays generated due to the interaction of highly energetic ions with shielding. To quantify the device's tolerance to a space-specific high-radiation environment, a radiation tolerance assessment is required. Testing of the displacement damage dose (DDD) effect, single event effect (SEE), and total ionizing dose (TID) effect are the main evaluation methods of radiation tolerance.

In this study, we investigated the displacement damage produced by irradiation of protons and Ni ions on GaN HEMTs by using several optical analysis methods, ultra-high voltage electron microscopy (HVEM) and device characteristic measurements.

2. Ion Irradiation Test

Conventional GaN HEMTs were grown on a 4H-SiC substrate. A Schottky gate electrode was formed using sputtered TaN and Au layers(1). 3 MeV protons and 18 MeV Ni were irradiated using an ion accelerator system(2) at the National Institutes for Quantum and Radiological Science and Technology. Protons were irradiated on the entire surface of one of the GaN HEMTs and Ni ions were irradiated in a selected area of the GaN HEMT by using a focused ion beam.

3. Proton Ion Irradiation Effect

Before and after proton irradiation, the DC characteristics of the devices were measured. Figure 1 shows changes in the maximum drain current (I_{max}) with proton irradiation. At a low irradiation fluence of up to 1 × 10^{12} protons/cm^2, we found a slight increase of approximately 1% in I_{max}. This increase was recoverable, because the increased I_{max} decreased to the original value after annealing at 150°C. This result means that positive charges were trapped in the devices by proton irradiation in the low fluence region. No deterioration of I_{max} was found until the irradiation fluence exceeded 1 × 10^{13} protons/cm^2.

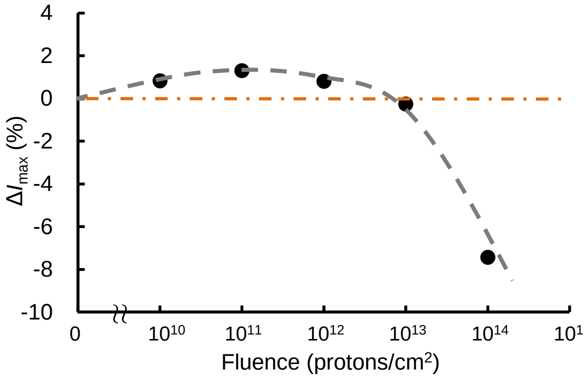

Fig. 1 Change in maximum drain current (I_{max}) with proton irradiation

With further irradiation of 1 × 10^{14} protons/cm^2, I_{max} decreased. Even in this case, critical failure such as a significant increase in gate leakage current and device breakdown did not occur. The cumulative proton irradiation amount on a satellite in geostationary orbit for 10 years is equivalent to approximately 7 × 10^{11} protons/cm^2 of 3 MeV protons. The influence on a device located inside the satellite is even smaller. This result indicates that GaN HEMT has sufficient resistance to protons in space environments.

4. Ni ion Irradiation Effect

In order to investigate the influence of displacement damage induced by ion irradiation on devices in more detail, we applied 18 MeV Ni ions as the irradiation particles.

Figure 2 shows changes in I_{max} with Ni ion irradiation. I_{max} was stable up to 1 × 10^{11} ions/cm^2 and started to decrease more than 2 × 10^{11} ions/cm^2 irradiation.

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Compared with the proton test results in Fig. 1, I_{max} in Fig. 2 started changing at a low irradiation fluence. The result indicates that the irradiation of 18 MeV Ni ions induced larger displaced damage than 3 MeV proton irradiation.

Figure 3 shows (a) reverse and (b) forward Schottky contact characteristics of the devices before and after the Ni ion irradiation. I_{max} decreased significantly by the Ni ion irradiation at a fluence of 5.5 × 10^{13} ions/cm^2 as shown in Fig. 1; however, the change of gate leakage current after the irradiation is negligibly small. These results indicate that the irradiations had no significant effects on the device reliability.

In order to examine the microscopic influence of Ni ion irradiation, we applied optical measurements such as photoemission microscopy (PEM), optical beam induced resistance change (OBIRCH) imaging, and photoluminescence (PL)(3). Electric field intensity, leakage current, and crystal quality can be observed by these methods. Figure 4 shows PEM, OBIRCH, and PL images before and after Ni ion irradiation of 7 × 10 ^{12} ions/cm^2. The irradiation area was located in the region indicated by the dotted square in Fig. 4. For the gate bias, −70 V was applied during the PEM observation and −10 V was applied during the OBIRCH observation. In all intensity distribution images after the Ni ion irradiation, the signal intensity uniformly decreased in the Ni-irradiated region. The decrease in each signal intensity indicates a reduction in the electric field intensity, a reduction in the leakage current and an increase in the recombination center, respectively. A spot-like signal, typically found in a device with a gate leakage current increase, cannot be found in the irradiated region. This indicates that no locally concentrated electric field or gate leakage was caused by the irradiation. This is consistent with the fact that no increase in the gate leakage current was observed in Fig. 3. Therefore, the results described above suggest that the Ni ion irradiation caused a uniform reduction in the carrier concentration, preventing a concentrated electric field that would lead to a significant increase in the gate leakage current.

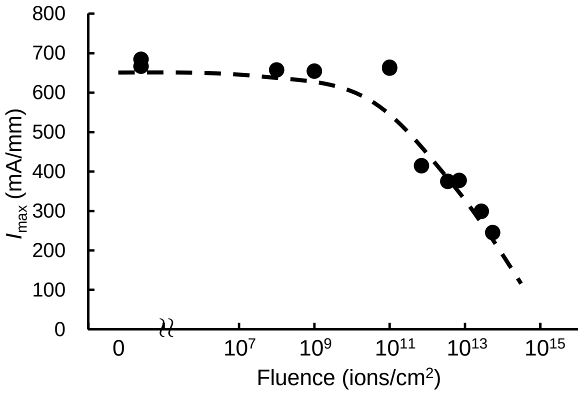
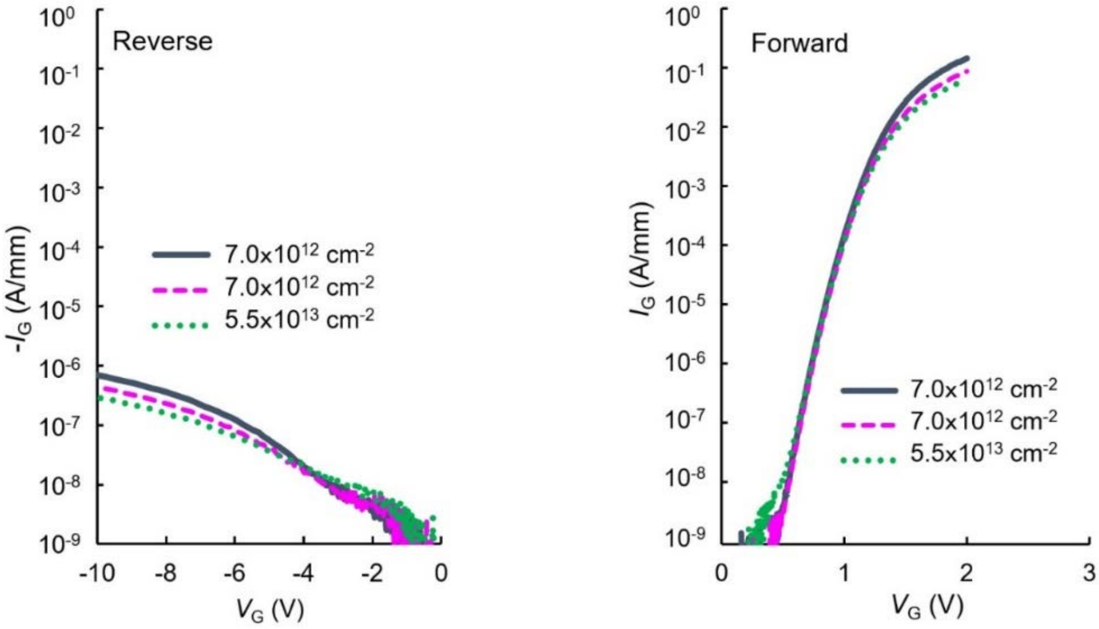


Fig. 2 Change in I_{max} with proton irradiation

We investigated the influence of ion irradiation on the GaN HEMT microscopically. When a semiconductor device is irradiated with high-energy ions, irradiation damage occurs due to the displacement of crystal atoms from regular lattice positions. Figure 5 shows a cross-sectional transmission electron microscopy (TEM) image taken after irradiation; for the observation, we irradiated the GaN HEMT with 2.8 × 10^{13} ions/cm^2 of Ni ions at 18 MeV. A sample thickness of 1.5 μm was observed by



(a) Reverse direction

(b) Forward direction

Fig. 3 (a) Reverse and (b) forward Schottky contact characteristics before and after 18 MeV Ni ion irradiation

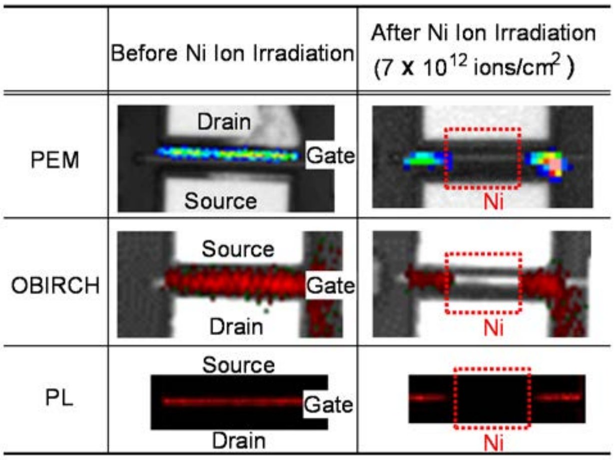


Fig. 4 PEM, OBIRCH and PL images before and after Ni ion irradiation

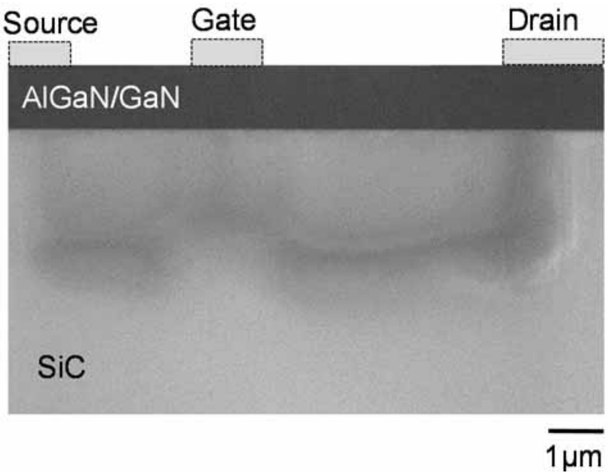


Fig. 5 Cross-sectional TEM image of the AlGaN/GaN HEMT after Ni ion irradiation

an acceleration voltage of 2 MV using an ultra-high voltage electron microscope (H-3000)(5). A darker shape was observed in the SiC substrate region below the AlGaN/GaN layer, corresponding to the irradiation damage. The damage reached a depth of approximately 4 μm in the SiC substrate. The damage was also found under the gate electrode, although the damage slightly shifted to the gate electrode. The shift indicates that the energy of Ni ions is decreased by the gate electrode.

The lattice defects were supposed to be created near the AlGaN/GaN channel layer, causing a decrease in the carrier concentration and mobility. This is likely to have caused a decrease in the drain current. Figure 5 shows no line-type defects caused along the ion track. It is consistent with the results of no increase in gate leakage current and electric field concentration.

5. Conclusion

Irradiation experiments of ions to GaN HEMTs indicate that the device would be stable up to a fluence of 1×10^{13} protons/cm^2 for 3 MeV proton and 1×10^{11} ions/cm^2 for 18 MeV Ni ions. Excessive ion irradiation caused a decrease in the drain current, but did not cause a concentrated electric field or an increase in the gate leakage current. GaN HEMTs had sufficient radiation tolerance in space environments.

References

(1) Yamasaki, T., et al.: A 68% Efficiency, C-Band 100W GaN Power Amplifier for Space Applications, Proc. Microwave Symp. Dig. MTT-S Int., 1384–1387 (2010).

(2) Onoda, S., et al.: Enhanced Charge Collection by Single Ion Strike in AlGaN/GaN HEMTs, IEEE Trans. On Nuclear Science, 60(6), 4446–4450 (2013).

(3) Sasaki, H., et al.: Irradiation Effect of Ions on AlGaN/GaN HEMTs, ROCS Workshop Proceedings, 59–67 (2016).

(4) Ziegler, J.F., et al.: The Stopping and Range of Ions in Solids, Vol. 1, New York: Pergamon Press (1985).

(5) Advanced Characterization Nanotechnology Platform, Research Center for Ultra-High Voltage Electron Microscopy, Osaka University, http://www.uhvem.osaka-u.ac.jp/nanoplatform-kouzoukaiseki/index.html.