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II. 3. Proton Irradiation Effects for GaN Schottky Diode

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III-N semiconductors have attracted much interest with their excellent electrical and optical properties. Among them, gallium nitride (GaN) has been applied optoelectronic and high power devices with the characteristics of thermal, mechanical and chemical stability^{1,2}. In addition, the GaN based devices are expected to have high radiation hardness due to its lower generation rate of charge carriers and higher atomic displacement energy. Thus, the GaN based devices are considered to be really useful in harsh radiation environments. The radiation hardness of the III-N materials has been investigated experimentally from the various points of view³⁻⁷. We have examined the resistance for the radiation damage with the GaN Schottky diode, irradiating high energy electron and proton beams. We found that no serious degradation in the diode characteristics was observed even after irradiating $10^{14}\sim 10^{15}$ protons/cm²⁸⁻¹⁰. In this study, we have irradiated the GaN Schottky diodes with proton beam to verify the radiation tolerance suggested in our previous experiments. Then, we tried to understand the proton irradiation effects more precisely by mean of the measurement of some electrical properties. Moreover, we examined the relaxation process of the characteristics over a long time period after the irradiation.

The epitaxial GaN layer was grown on n-type SiC substrate through the medium of buffer layer. The cross-sectional and top views of GaN Schottky barrier diode used in this study are shown in Fig. 1. The thickness of the undoped GaN (u-GaN) layer was 1800 nm. The diode chip was mounted on the thin (t=0.6 or 1.2 mm) FR-4 universal board as shown in Fig. 2. We prepared several samples and each sample was irradiated with protons with different fluence. After the irradiation, the samples were kept in the room temperature and

the characteristics were measured with certain time intervals.

The energy of the proton beam was 70 MeV in this experiment. The beam current was set to be ~ 100 nA. In prior to the irradiation to the sample, an aluminum foil was exposed to the beam, then, the radioactivity of meshed area on the foil was measured by a imaging plate to obtain the beam profile. Assuming that the beam condition was stable over the experiment periods, the profile measurement was employed just once in. The beam intensity profile obtained by this method is shown in Fig. 3. The target diode was placed at the center of the beam. The proton fluences on the diode were determined considering the beam current and the profile. The irradiated proton fluences for each sample are summarized in Table 1.

Figure 4 shows the current-voltage (I-V) characteristics before and after irradiation for the samples 1 and 2. The high energy proton irradiation causes the atomic displacement in the crystal and the intrinsic defects affect the electric property of the devices such as increase of noise, change in electric conductivity, lowering the break down voltage and so on. We did not see obvious increase in the reverse dark currents or change in the breakdown voltage for the fluence up to 10^{14} protons/cm². Figure 5 shows the I-V characteristics for the sample 3-5 irradiated with the order of $\sim 10^{15}$ protons/cm². Although the individual sample has a variety in the I-V characteristics even before irradiation, the dark currents increased by a factor of 10^3 - 10^4 . The proton irradiation can induce the trap states in the material which affect the electric conductivity. As the result, the dark currents can increase. In terms of the time variation of the characteristics, the dark currents seem to get smaller with lapse of time. This recovery may be associated with the defect annihilation process at low temperature. Unstable behaviors in the reverse currents were observed for the samples 4 and 5, and they almost disappeared 181 days after irradiation. These phenomena might indicate the forming and vanishing of the localized level at the metal-semiconductor interface.

Figure 6 shows the capacitance-voltage (C-V) characteristics for the samples 3 and 4. The capacitance decrease was observed significantly after irradiation and the change is likely to be larger with higher fluence. Formation of the trapping level was supposed to cause the change of the capacitance. Additionally, the fluctuations of the capacitance as a function of supplied biases were recognized at 50 days after irradiation, and such behavior disappeared at 82 days after irradiation. This fluctuation might be concerned with the unstable behavior in the I-V plots. The effective density of the impurity carrier N_d can be

derived by the C-V characteristic by the following formula;

$$N_d = \frac{-2}{q\epsilon_s\epsilon_0 A^2 \left(\frac{d(1/C^2)}{dV} \right)}$$

where, q is electron charge magnitude, ϵ_s is relative dielectric constant of GaN, ϵ_0 is dielectric constant in the vacuum and A is the area size of the electrode. The calculated densities are shown in Table 2. Note that we could not determine the density from the data after 50 days of irradiation because the fluctuation of the C-V curve was significantly large. We have found that the density before irradiation was larger than that after irradiation, and it seemed to decrease with increase of the time after irradiation. The density is related to the number of defects induced by the radiation, in principle. Now it is assumed that considerable defects were generated by the proton irradiation and the electrically active carries in the original sample were disappeared. Then, the remaining defects were vanished with annealing effect at room temperature so that the capacitance decreased gradually. This assumption can be clarified by quantitative measurement of the trapping level and the relaxation process, which is an important issue in the future study.

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Table 1. Proton fluences for each sample.

	Fluence (protons/cm ²)
Sample 1	8.5×10^{12}
Sample 2	5.1×10^{13}
Sample 3	1.2×10^{15}
Sample 4	3.1×10^{15}
Sample 5	6.1×10^{15}

Table 2. Effective density of impurity calculated by $1/C^2$ -V plots.

	Fluence (protons/cm ²)
Sample 1	8.5×10^{12}
Sample 2	5.1×10^{13}
Sample 3	1.2×10^{15}
Sample 4	3.1×10^{15}
Sample 5	6.1×10^{15}

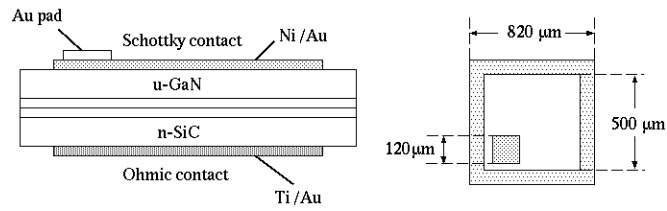


Figure 1. GaN Schottky diode.



Figure 2. The diode chip mounted on FR-4 universal board.

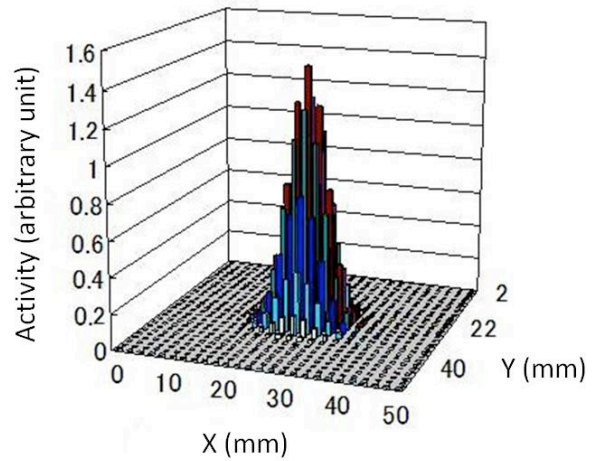


Figure 3. The beam profile measured by a imaging plate exposed with activated aluminum foil.

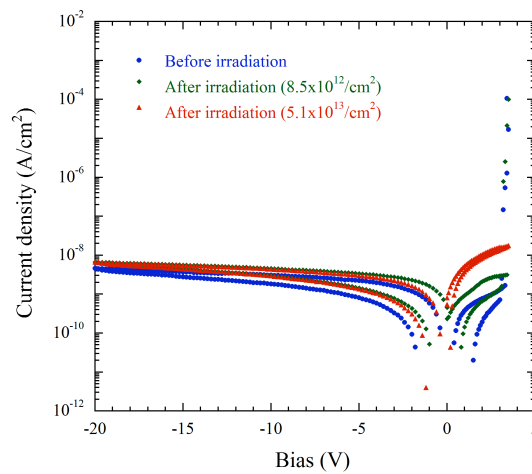


Figure 4. I-V characteristics before and after irradiation with fluences of 8.5×10^{12} (sample 1) and 5.1×10^{13} (sample 2) protons/cm².

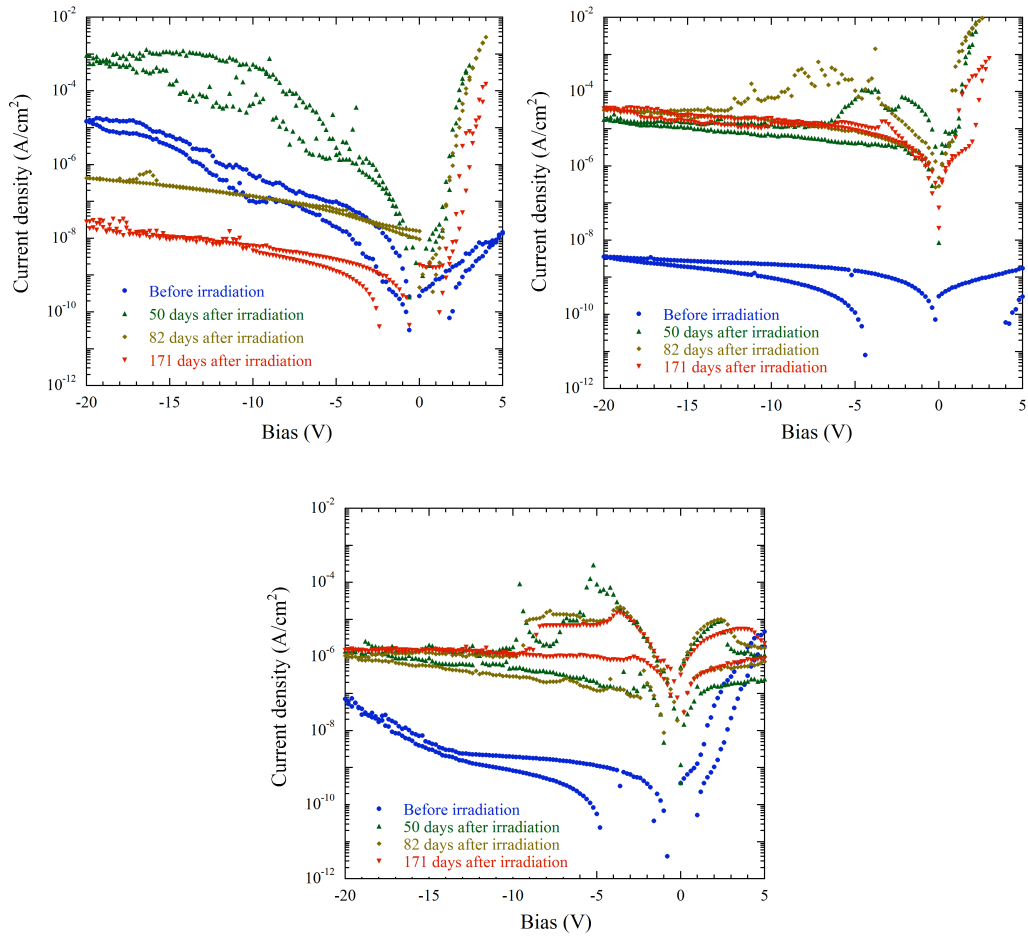


Figure 5. I-V Characteristics before and after irradiation with fluences of 1.2×10^{15} (top-left), 3.1×10^{15} (top-right) and 6.1×10^{15} (bottom) protons/cm².

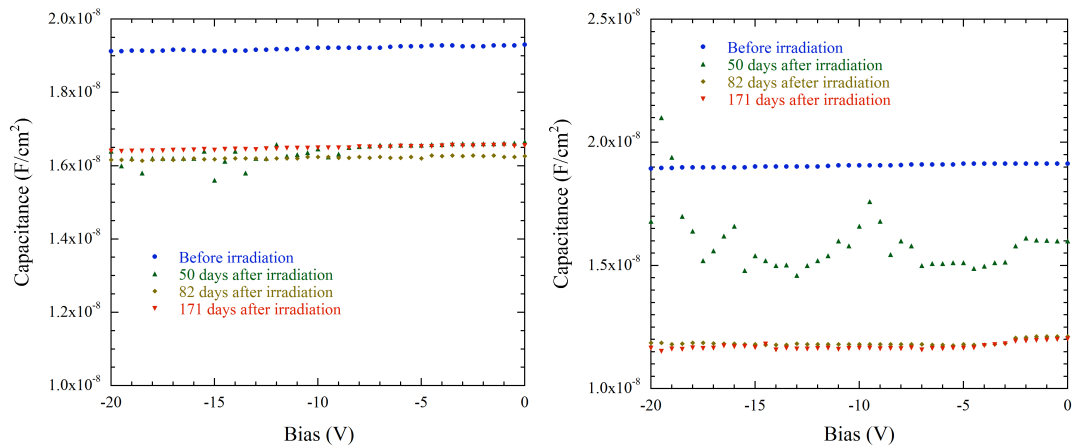


Figure 6. C-V Characteristics of sample 3 (left) and sample 4 (right) before and after irradiation.