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Effects of high-energy proton and electron irradiation on GaN Schottky diode

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ABSTRACT

We performed high-energy proton and electron irradiation on a GaN Schottky diode and investigated the effects on its electrical properties. No significant changes in the dark current or breakdown voltage of the diode were observed for fluences up to $\sim 10^{14}$ protons/cm^2. The currents increased by a factor of $\sim 10^3$ at a fluence of $\sim 10^{15}$ protons/cm^2. The currents also fluctuated unstably at these fluences but this unstable behavior was not observed after a few months. Intrinsic defects may have been induced by particle irradiation and some of them annealed through a relaxation process. Under electron irradiation, the dark currents did not show a notable increase even with the fluence of $\sim 10^{16}$ electrons/cm^2.

1. Introduction

III-N semiconductors have attracted much interest because of their excellent electrical and optical properties. Among them, gallium nitride (GaN) has been applied in optoelectronic and high-power devices having thermal, mechanical, and chemical stability [1–3]. GaN is also interesting in applications for sensors of ionizing radiation because of its high density and high threshold energy for creating intrinsic charge carriers, which are expected to make it useful in energy spectrometers and imaging devices. These sensors are often used in harsh radiation environments such as in high-energy collider experiments. In these experiments the sensor is used for precision tracking and placed near the beam interaction point, where a huge amount of radiation is emitted. Under these conditions, radiation-induced damage to the material becomes a serious problem. Therefore, the device must be highly resistant to such damage. To develop a new radiation sensor, several semiconductor materials have been investigated to replace Si, which is the primary material used in existing semiconductor radiation sensors [4–6]. The effects of the particle irradiation on a semiconductor device depend in principle on the energy loss of the particles irradiating the materials in both ionizing and non-ionizing processes. In particular, the non-ionizing energy loss (NIEL) can induce intrinsic defects and atomic displacement in the crystal, which can affect the electrical properties of the device. When the device is used as an ionizing sensor, for example, the signal-to-noise ratio decreases, and the signal charge can fluctuate because of an increase in the dark currents and a decrease in the charge collection efficiency. GaN is a good candidate as a sensor material due to its lower charge carrier generation rate and higher atomic displacement energy. The radiation hardness of III-N materials, including GaN, has been investigated experimentally from various points of view [7–11]. The results of those studies have suggested that these materials may have a high resistance to radiation damage. To confirm the results, it is still necessary to perform beam irradiation tests under various conditions because the effects of damage depend on parameters such as the device structure, type and energy of irradiating particles, and operating conditions.

In this study, we fabricated GaN Schottky diodes, irradiated them with high-energy proton and electron beams, and investigated the effects on their electrical characteristics.

2. Experiment

We used GaN epitaxial material grown on an n-type SiC substrate having a diameter of 2 in. through the medium of a buffer layer. The SiC layer plays a role of the foundation for a GaN epitaxial layer and it is supposed to be equivalent to a resistance in the diode circuit. The GaN and the SiC layers were 1800 nm and 280 nm thick, respectively. The epitaxial layers of GaN tested here

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are not of sufficient thickness to be fabricated into useful detector elements. Development of a technology to fabricate such a useful substrate is still underway [12–14]. In this study, we used a high quality GaN epitaxial layer currently available which was originally designed for photodiodes.

We deposited Ti and Au layers on the SiC and annealed the sample to make the contact ohmic. We checked electric conductivity of the sample and confirmed formation of an ohmic contact. Then, a Ni film was deposited on the GaN face to form the Schottky contact. These electrodes were deposited by physical vapor deposition. The diode was originally designed as a photodiode, and the thickness of the Schottky electrode was controlled to obtain light transparency. After the electrode was deposited, the diodes were diced into $820 \times 820\ \mu m^2$ chips, and each diode chip was bonded onto an FR-4 PCB or a metal stem. Cross-sectional and top views of the diode sample used in this study are shown in Fig. 1.

The sample diodes were irradiated with a proton beam. The irradiation test was conducted at CYRIC, Tohoku University, using a 20 MeV proton beam with a current of ~100 nA. We prepared several diodes and irradiated them with protons at different fluences. Before the sample was irradiated, an aluminum foil was exposed to the beam, and the radioactivity of the foil was measured by an imaging plate to obtain the beam profile. Assuming that the beam conditions were stable over the irradiation periods, the profile was measured just once. 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. In addition, electron beam irradiation was performed in this study using the 150 MeV electron beam from the accelerator at the Laboratory of Nuclear Science, Tohoku University. In both the proton and electron irradiation tests, no voltage was applied to the target diodes, and the diodes were not electrically connected during irradiation. The samples were kept at room temperature during the experiment. The radiation induced damage of a solid state material is usually discussed considering the NIEL of an irradiated particle. The NIEL for a silicon has been well studied, and estimated to be $7\ keV\ cm^2\ g^{-1}$ for a 20 MeV proton and $0.1\ keV\ cm^2 g^{-1}$ for a 150 MeV electron, and NIEL for other semiconductor materials is considered to be the same order of magnitude [15–17].

In this study, the current–voltage (I–V) characteristics were measured pre- and post-irradiation by an ultrahigh-resistance meter (ADVANTEST; R8340) in order to evaluate the effects of particle irradiation. The dark currents, breakdown voltage, and behavior of the forward currents were characterized. In the I–V measurement, we set the diode into a test-fixture and measured currents increasing the forward bias from 0 to +5 V with 0.1 V step. After the forward current measurement, we took off and set the sample into the test-fixture with opposite polarity and measured currents increasing the reverse bias from 0 to −20 V with 0.1 V step. Note that we only measured the reverse current for the sample irradiated with electron beam in the present study.

Table 1
Irradiated proton fluences for each sample.

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

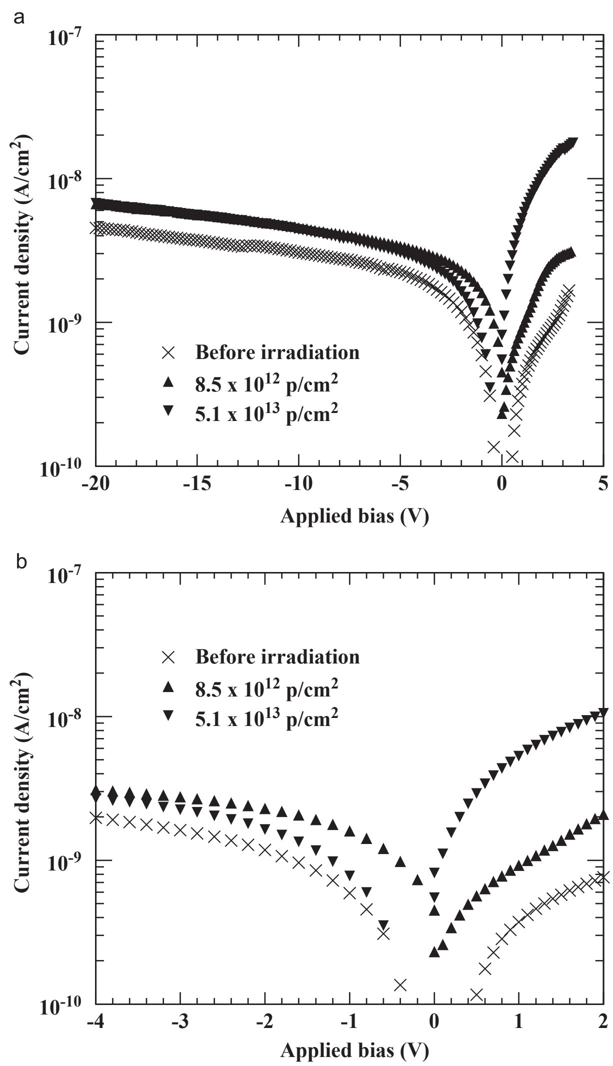

Fig. 2. (a) I–V characteristics before (×) and after irradiation at fluences of 8.5×10^{12} (sample #1: ▲) and 5.1×10^{13} (sample #2: ▼) (top), (b) an enlargement of the applied bias between −4 V and +2 V (bottom).

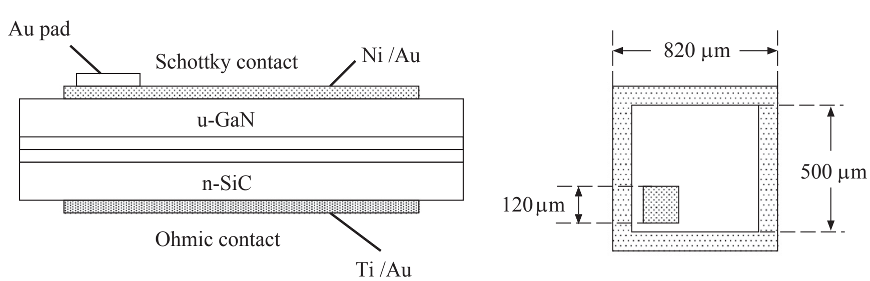

Fig. 1. GaN Schottky diode.

The I–V measurement was performed just after irradiation for samples #1 and #2, and at 50 days after irradiation for samples #3 and #4. Because samples #3 and #4 became highly radioactive under irradiation with a large amount of protons, we needed to wait until the activity became reasonably low. In addition, the measurements for these samples were iterated at 82 days and 171 days after irradiation to investigate the change in the characteristics with time. The samples were kept in a dry-keeping cabinet in the air-conditioned laboratory where the temperature was controlled at 20–25 °C, in the term between the measurements.

3. Results and discussion

Fig. 2 shows the I–V characteristics before and after proton irradiation at fluences of 8.5×10^{12} protons/cm^2 (sample #1) and 5.1×10^{13} protons/cm^2 (sample #2), and the enlargement of the applied bias between −4 V and +2 V. We did not observe a significant increase in the reverse dark currents or a change in the breakdown voltage at these fluences. Moreover, we noticed that the forward and backward currents were comparable for the sample before irradiation, as shown in Fig. 2(b). We could speculate that there are interface states in the original sample which cause suppression of the forward currents. This might be a reason why a diode characteristic was not seen for the sample before irradiation. In contrast, the forward currents for the sample after irradiation increased. The forward–backward current ratios at the bias of ± 2 V for non-irradiated and irradiated samples are shown in Table 2. It is assumed that the probability of the carrier recombination became small due to vanishing of the interface states by the proton irradiation. This assumption could be verified quantitatively by measurement of the distribution of interface states. This is an important issue for the future study.

Table 2
Forward–backward current ratio at bias of ± 2 V.

Sample	Forward–backward current ratio
Non-irradiated sample	0.6
Irradiated 1.5×10^{12}	0.9
Irradiated 8.5×10^{12}	6.4

Fig. 3 shows the I–V characteristics for samples #3 and #4 irradiated with on the order of $\sim 10^{15}$ protons/cm^2. Although the individual samples exhibited variation in the I–V characteristics even before irradiation, the dark currents increased by a factor of 10^3–10^4 after irradiation. While there is a difference between the samples, the large change in current may be attributed to irradiation. The induced defects may have had a significant effect on the electrical properties at these fluences. The behavior of the forward currents also changed, as observed in samples #1 and #2. In addition, the reverse currents fluctuated unstably under an

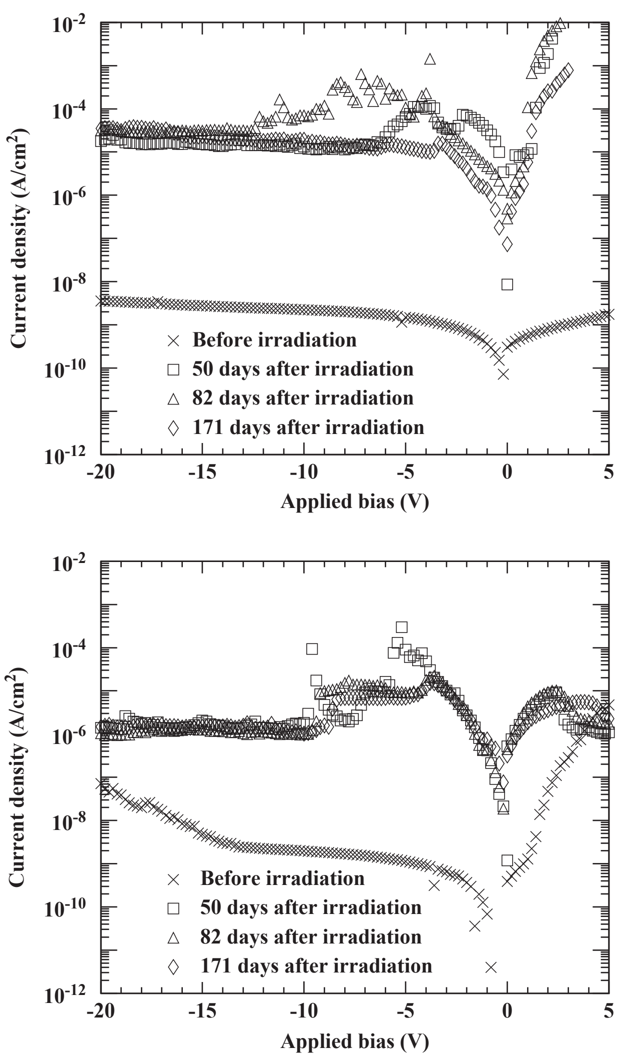

Fig. 3. I–V characteristics of samples #3 and #4 before and 50 days (□), 82 days (△), and 181 days (◇) after irradiation.

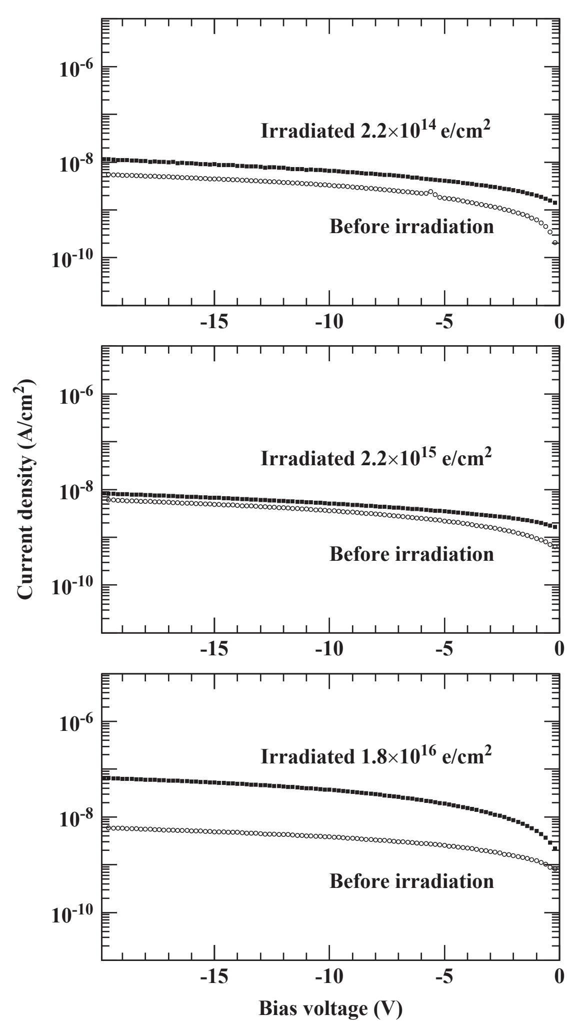

Fig. 4. I–V characteristics before and after the electron irradiation.

applied bias of −10 to 0 V, and they relaxed with time. It might be supposed that these phenomena indicate the vanishing of the localized levels generated by proton irradiation.

Fig. 4 shows the I-V curves before and after electron beam irradiation at each fluence. No significant increase in the dark currents was observed even at fluences of greater than 10^{16} electrons/cm^2. The breakdown voltage was still more than 20 V.

4. Summary

We investigated the effects of irradiating GaN Schottky diodes with high-energy protons and electrons. The electrical properties of the diodes did not change significantly under fluences of up to 10^{14} protons/cm^2 and $\sim 10^{16}$ electrons/cm^2. For the sample irradiated with $\sim 10^{15}$ protons/cm^2, the dark currents increased by a factor of $\sim 10^3$. At these fluences, the currents exhibited unstable fluctuations, and this behavior relaxed after a few months. This might be attributed to the generation and annihilation of induced defects. Further quantitative study, such as measurements of the level of induced defects and the interface state density, will confirm this characteristic. It will be also necessary to measure actual detection performance in order to evaluate radiation hardness of the material.

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