Effects of Proton Irradiation on the Magnetoelectric Properties of 2DEG AlGaN/GaN Micro-Hall Sensors

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Abstract. The effects of irradiating AlGaN/GaN micro-Hall sensors with 380 keV protons on were investigated by magnetoresistance measurements. The sheet resistance increased after irradiation with a proton dose of 1x10^{13} cm^{-2} due to the decrease of carrier mobility rather than the decrease of sheet carrier density. Our experiments showed that AlGaN/GaN two-dimensional electron gas (2DEG) structures are good strong candidates for Hall sensors operable in harsh radiation environments.

1. Introduction

Hall effect magnetic field sensors fabricated using compound semiconductors such as InSb and GaAs are widely used in the electronics industry for monitoring rotation in equipment such as optical memory disks and for banknote authentication in vending machines. More recently, the availability of gallium nitride-based heterostructures has enabled the fabrication of high performance AlGaN/GaN-based micro-Hall sensors operable at , with reports of applications including medical diagnostics [1]. Recent industrial trends indicate increasing demand for Hall sensors for monitoring magnetic fields in outer space and nuclear power stations, which is extremely challenging because sensors for such applications must withstand extreme fluctuations in temperature as well as harmful radiation in these environments.

The irradiation of semiconductors such as silicon and GaAs with high energy electrons and protons, causes an increase of their resistivity due to the generation of defects in the semiconducting crystals. This behavior has also reported to occur in GaN [2,3]. The effects of proton irradiation on packaged AlGaN/GaN heterojunction-field effect transistors (HFET) have also been reported, with emphasis on irradiation effects on the controllability of Schottky gates [4,5]. To our knowledge, the study of proton irradiation effects on AlGaN/GaN heterostructure for Hall sensors without protective packaging has not been previously reported. Here, we report on the effect of proton irradiation on the magnetoelectric properties of micro-Hall sensors fabricated using 2DEG-AlGaN/GaN heterostructures. The resistivity,
sheet carrier density, and electron mobility of the structures were investigated by Hall effect measurements after proton irradiation, and potential application of AlGaN/GaN for Hall sensors operable in harsh radiation environment is discussed.

2. Experimental

Fig. 1 shows the structure of the AlGaN/GaN samples used in this study. The high electron mobility transistor (HEMT) structures were grown by metal organic chemical vapor deposition (MOCVD) and consist of an unintentionally doped AlGaN layer and a two-dimensional electron gas (2DEG) at the AlGaN/GaN heterointerface due to highly polar nature of AlGaN and GaN. The sheet carrier density and electron mobility at room temperature were $8 \times 10^{12}$ cm$^{-2}$ and 1600 cm$^2$/Vs, respectively. We also studied devices with a Si doped top AlGaN layer.

These AlGaN/GaN heterostructures were used to fabrication four-terminal micro-Hall devices with active regions ranging from 1\(\mu\)m x 1\(\mu\)m to 5\(\mu\)m by photolithography. Details of the fabrication process are given in Ref. 1. Notably, the active areas of the resulting Hall sensors were not protected by any form of packaging.

The micro-Hall sensors were irradiated with 380 keV protons using an ion-implantation facility at Takasaki Ion Accelerators for Advanced Radiation Application (TIARA), JAERI, in Japan. The samples were placed in a vacuum chamber and irradiated with a range of proton doses. According to Stopping and Range of Ions in Matter (SRIM) simulations for calculation of the proton projection range, 98% of the implanted protons at 380 keV penetrated to a distance of 2\(\mu\)m through the epitaxial nitride layers [6]. Thus the implantation of protons is expected to have a limited effect on the electrical characteristics of the 2DEG, which is 25 nm from the surface.

We prepared samples from same AlGaN/GaN wafer for each proton irradiation conditions in range 1\(x\)10$^{11}$ cm$^{-2}$ to 1\(x\)10$^{16}$ cm$^{-2}$. The samples were not annealed before during or after proton irradiation. The sheet resistance, 2DEG electron mobility and sheet carrier density were measured by the Hall effect using a constant current drive at room temperature.

3. Results and Discussion

Fig. 2 shows the variation of the sheet resistance with dose of proton irradiation. The sheet resistance increased with increasing proton dose, which suggests the generation of crystalline damage into the AlGaN/GaN structure. A marked increase of sheet resistivity was found above doses of 1\(x\)10$^{14}$ cm$^{-2}$. It was not possible to measure the electrical characteristics of samples irradiated with 1\(x\)10$^{15}$ and 1\(x\)10$^{16}$ cm$^{-2}$ because they exhibited extremely high resistance.
Fig. 3(a) shows the variation of the 2DEG electron mobility and sheet carrier density change with proton dose. Although there was a slight scatter the data point, the electron mobility gradually decreased with increasing proton dose. This tendency was also found in samples with intentionally doped AlGaN layers. In contrast to the electron mobility, the sheet carrier density shown in Fig. 3(b) remained constant with a value similar to the non-irradiated reference sample up to a proton dose of $1 \times 10^{14}$ cm$^{-2}$.

The effects of proton irradiation on the crystallinity of AlGaN/GaN heterostructures were examined by X-ray diffraction (XRD) measurements as shown in the in $2\theta-\omega$ scan in Fig. 4. The results show the XRD peaks of the reference and the $1 \times 10^{14}$ cm$^{-2}$ dose proton samples, which are, assigned as XRD peaks from the GaN layer based on the diffraction angles. These results showed that the XRD peaks remained after irradiation with a dose of $1 \times 10^{14}$ cm$^{-2}$. It should be noted that an additional shoulder in
lower angle side of irradiated sample was observed. A similar shoulder was reported after 2 MeV irradiation by Sonia et al [4], and attributed to the generation of interstitial defects in the heterostructure. Although our XRD results suggest the generation of proton irradiation effects in our AlGaN/GaN structures, it is difficult to directly connect the XRD results with the electrical characteristics because the electrical characteristics are sensitive to the 2DEG region, whereas the XRD signal is from whole of the sample. We are planning further studies using depth sensitive characterization techniques such as energy dependent cathodoluminescence.

Our experimental results showed that proton irradiation leads to increases in the sheet resistivity of 2DEG, particularly for proton dose of $1 \times 10^{14}$ cm$^{-2}$ due to a decrease in the electron mobility of AlGaN/GaN heterostructure. Several groups have reported on the effects of proton irradiation on n-GaN. For example, Auret et al reported the formation of electron traps in n-GaN after 2 MeV proton irradiation based on deep level transient spectroscopy (DLTS) measurements. [2]. They also reported dramatic reduction of the carrier density in n-GaN irradiated by 1 MeV protons [3]. In Ref.[3] a gradual decrease of the carrier density was reported after relatively low proton dose of $2 \times 10^{12}$ cm$^{-2}$, which is two-orders of smaller than our results. Similar gradual but clear reductions in carrier density of n-GaN were reported by Polyakov et al for 350 keV proton irradiation at a dose of $8 \times 10^{13}$ cm$^{-2}$ [7].

Our results in Fig.3(b) show a constant carrier density after irradiation with a proton dose of $1 \times 10^{14}$ cm$^{-2}$. Sonia et al also reported the conservation of sheet carrier density in AlGaN/GaN heterostructures by 2 MeV proton irradiation up to the dose of $1 \times 10^{14}$ cm$^{-2}$ [4]. A possible reason for the high stability of carrier density in AlGaN/GaN under high doses of proton irradiation may be the higher carrier concentration of the 2DEG. The initial carrier density reported for n-GaN was in range of $5-12 \times 10^{17}$ cm$^{-3}$ but in contrast the corresponding carrier density of the 2DEG in AlGaN/GaN structures is $10^{19}$ cm$^{-3}$ if one assumes the thickness of 2DEG to be 10 nm. Thus, active carriers still remain in the higher carrier density sample remains even after irradiation with high dose of protons. Our results suggest that the high sheet carrier density of AlGaN/GaN structures is an important factor for applications of such Hall sensors in radiation environments. As shown in Figs. 3(a) and (b) the variation of electron mobility and sheet carrier density were not sensitive to Si doping of the top AlGaN layer. These results indicate that the sheet carrier density and related electrical transport properties of AlGaN/GaN 2DEG Hall sensors after the proton irradiation is dominated by polarization field effects at the heterointerface rather than Si doping of the AlGaN layer.

The increase of sheet resistance of the samples shown in Fig.2 above proton doses of $1 \times 10^{13}$ cm$^{-2}$ is thought to be due to a decrease of electron mobility rather than a decrease of the sheet carrier density. From SRIM simulations, 380 keV proton irradiation creates defects such as vacancies by displacement of atoms throughout the samples used in this study. The defect density for a proton dose of $10^{14}$ cm$^{-3}$
was roughly estimated to be $10^{18}$ cm$^{-3}$. This is similar to the nominal carrier density in 2DEG, thus potential fluctuations of defects may affect the electron transport but not the sheet carrier density, which is governed by macroscopic polarization field effects.

Finally, we would like to comment on an advantage of AlGaN/GaN Hall sensors in radiation environment. For Hall sensors operated in constant current mode the output Hall voltage, $V_H$, is given by $V_H = IB/qNd$, where $I$ is the driving current, $B$ is the magnetic field, $q$ is the electron charge, $N$ is the carrier concentration, and $d$ is the thickness. That is, the magnitude of $V_H$ is independent from the electron mobility. Thus AlGaN/GaN Hall sensors can be used in hard radiation environments under constant current mode operation because the density of the 2DEG is relatively unaffected even at high proton fluences. On the other hand, in case of operation under constant voltage mode, because $V_H$ is a function of electron mobility, the sensitivity of the Hall sensor is affected by irradiation induced damage, as shown in Fig. 3(a). Another advantage of AlGaN/GaN Hall sensors is their higher tolerance against the proton irradiation compared with other heterostructures. Wang et al reported 0.5 MeV proton irradiation effects on AlGaAs/GaAs heterostructures [8]. Clear decreases of sheet carrier density were seen after a proton dose of $10^{11}$ cm$^{-2}$, which is much smaller than the doses used in this study on AlGaN/GaN. Our results show that AlGaN/GaN Hall sensors are promising for applications in harsh radiation environments.

4. Conclusion

We investigated the effects of 380 keV proton irradiation on the magnetoelectric properties of AlGaN/GaN micro-Hall sensors. We observed an increase of the sheet resistance after the proton dose of $1x10^{13}$ cm$^{-2}$, which we explained as being caused by a decrease of the carrier mobility rather than sheet carrier density. Our results show that the AlGaN/GaN 2DEG structures are good candidates for the fabrication of Hall sensor operated in harsh radiation environments.

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