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Characterization of AlGaN/GaN HEMT irradiated at 5 keV and 25 MeV proton energies

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AlGaN/GaN high electron mobility transistors(HEMT) were irradiated at 5 keV and 25 MeV proton energies. Current-voltages were compared before and after proton irradiation. As expected from simulation results, 5 keV protons severely damaged the transistors' performance compared to 25 MeV protons. Also, the effects of both low and higher fluencies were compared. Source-Drain currents were dramatically decreased under a higher fluency. Due to the extremely thin 2-Dimensional Electron Gas and the high displacement threshold energy, AlGaN/GaN HEMTs have great potential for applications in earth orbit.

Key words: Gallium Nitride, High Electron Mobility Transistor, Proton, Irradiation.

Introduction

III-nitrides have numerous applications in wireless communications, power electronics, optoelectronics, high temperature gas sensors, and space aircraft due to their large bandgap (3.39eV at room temperature), high breakdown field (~5 $\times$ 10^6 V/cm), direct bandgap and exceptional radiation hardness [1-6]. In space applications, high energy protons up to a few hundreds MeV in the Van Allen belts can cause severe damage to electronic devices, and dramatically shorten the device lifetime [7]. Therefore, reliability tests under high energy proton irradiation on earth are essential to pave a way to successful space missions. AlGaN/GaN HEMTs have been intensely researched for use in high power, high frequency, and high temperature applications [8-9]. Moreover, the unparalleled radiation hardness of III-nitrides makes AlGaN/GaN HEMT an excellent candidate for space applications (for example, space satellite weather forecasting systems) compared with conventional GaAs- based transistors and Si-based transistors [6]. Furthermore, the 2DEG (2-dimensional electron gas) of the HEMT structure is extremely thin. Therefore, the probability that high energy protons will create defects inside 2DEG is very low [10].

Previously, Luo *et al.* reported the degradation of current-voltage characteristics after exposure of AlGaN/ GaN HEMT to ^{60}Co gamma-rays [11]. In addition, Hu *et al.* studied the influence of proton irradiation with energies between 1.8 MeV and 105 MeV energy on AlGaN/GaN HEMT [12].

Here, we report the I_{DS}-V_{DS} characteristics at various gate bias before/after proton irradiation at 5 keV (2 $\times$ 10^{13} cm^{-2}, 2 $\times$ 10^{16} cm^{-2} fluencies) and 25 MeV energy(2 $\times$ 10^9 cm^{-2}, 2 $\times$ 10^{12} cm^{-2} fluencies). The radiation tolerance results from these samples will be very helpful in understanding the degradation mechanism and improving the device reliability under high energy proton irradiation.

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Experiments

$Al_{0.3}Ga_{0.7}N$/GaN was grown on c-plane Al_2O_3 substrate by a MOCVD(Metal Organic Chemical Vapor Deposition) technique, where the thickness of AlGaN was 25 nm and the thickness of GaN was 3 μm. To create the mesa structure, an inductively coupled plasma system was employed. Then, an electron-beam deposition technique was used to deposit ohmic metallization (Ti/Al/Pt/Au), which was defined by photo-lithography. After it was annealed at 750°C for 30 seconds under a nitrogen ambient, gate metallization (Pt/Au) was deposited, followed by final metallization (Ti/Au) deposition. Finally, the devices were passivated using silicon nitride in a PECVD system (Plasma-Enhanced Chemical Vapor Deposition). Schematic diagram is shown in Fig. 1.

Proton irradiation experiments were performed at the

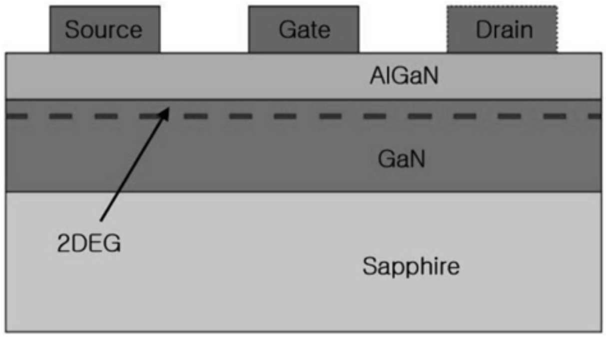

Fig. 1. Schematic Diagram of AlGaN/GaN HEMT.

facility of KAERI (Korea Atomic Energy Research Institute). Proton beam energies of 5 keV and 25 MeV were used to compare the effects of different beam energies. Also, various fluencies were compared to understand the effects of total dose. For the 5 keV proton irradiations, the fluencies were about 2 × 10^{13} protons/cm^2 (18 seconds) and 2 × 10^{16} protons/cm^2 (1092 seconds) at a pressure of 5 × 10^{-5} Torr (0.0067 Pascal). For the 25 MeV proton irradiations, the fluencies were about 2 × 10^9 protons/cm^2 (4 seconds) and 2 × 10^{12} protons/cm^2 (3728 seconds) at 1 atm. To compare experimental results with simulation results, the same conditions were simulated using SRIM2006 software [13]. Current-voltage characteristics(I_{DS}-V_{DS}) at various gate biases(V_{GS}) were compared using an Agilent 4155C parameter analyzer before/after proton irradiation at various fluencies. All I-V characteristics were measured at room temperature (25°C) to avoid post-annealing effects.

Results and Discussion

Fig. 2 shows the I_{DS}-V_{DS} characteristics at $V_{GS} = -6$, −4, −2 and 0 at lower fluencies. Before irradiation, AlGaN/GaN HEMT showed good modulation and the channel was fully depleted at $V_{GS} = -6$. After 25MeV proton irradiation for 4 seconds at a fluency of 2 × 10^9, I_{DS}-V_{DS} currents slightly dropped from 80.70 mA to 77.81 mA, which is a decrease of about 3.6%. After 5 keV proton irradiation, I_{DS}-V_{DS} currents dramatically dropped from 80.70 mA to 14.56 mA, which is a decrease of about 82%. At higher fluencies, the current drop is much more severe. The current-voltage characteristics at V_{DS} = 6V before/after proton irradiation are summarized in Table 1. The severe decrease at higher fluencies can be easily explained by the higher probability of creating defects when the sample is hit by more protons.

There have been many explanations of the mechanism of defect creation by high energy protons [7]. Compared with many other device structures, a HEMT is naturally resistant to high energy irradiation because the thickness of the 2DEG is so thin, most defects are created away from the 2DEG, which is the conducting layer of a HEMT [10]. Fig. 3(A), 3(B) show that by employing an extremely thin conducting layer, we can dramatically reduce the probability that the high energy protons will hit the conducting layer (2DEG). To prove this idea, SRIM simulation was performed at 5 keV and 25 MeV energies. As shown in Fig. 3(A) and 3(B), 5 keV caused much more damage to the 2DEG, which is just below the 25 nm thin AlGaN layer. I_{DS}-V_{DS} in Fig. 2(A) and 2(B) confirmed these simulation results.

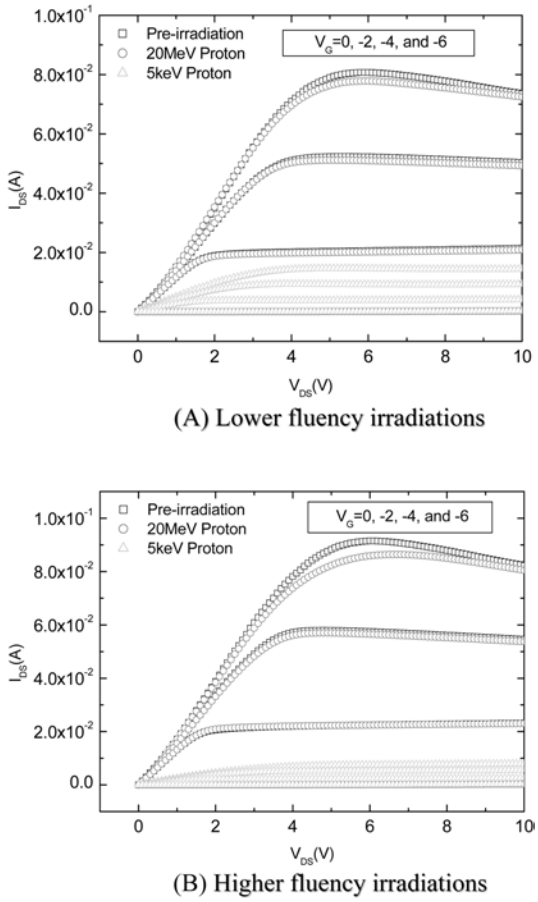

Fig. 2. Current-Voltage (I_{DS}-V_{DS}) characteristics at $V_{GS} = -6, -4, -2$ and 0 after proton irradiation.

The resistance to proton irradiation can also be explained by introducing a displacement threshold energy (T_d). According to empirical data, T_d is inversely proportional to the lattice constant.[12] Since the lattice constant of wurtzite GaN is a = 3.189Å c = 5.186Å, the radiation hardness of GaN is much better than that of Ge(5.646Å), GaAs(5.653Å) or Si(5.431Å).[12]

Therefore, GaN material system has great resistance to proton irradiation. In particular, the AlGaN/GaN HEMT structure with its extremely thin 2DEG is a potential candidate for use in space applications because of its strong radiation hardness.

Conclusions

In summary, AlGaN/GaN HEMT was fabricated using conventional photo-lithographic processes. Currents

Table 1. current-voltage characteristics at V_{DS} = 6V before/after proton irradiation.

	Lower fluency	Higher fluency
Before irradiation	80.70 mA	91.47 mA
25 MeV irradiation	77.81 mA (3.6% decrease)	85.91 mA (6.1% decrease)
5 keV irradiation	14.56 mA (82% decrease)	7.49 mA (91.8% decrease)

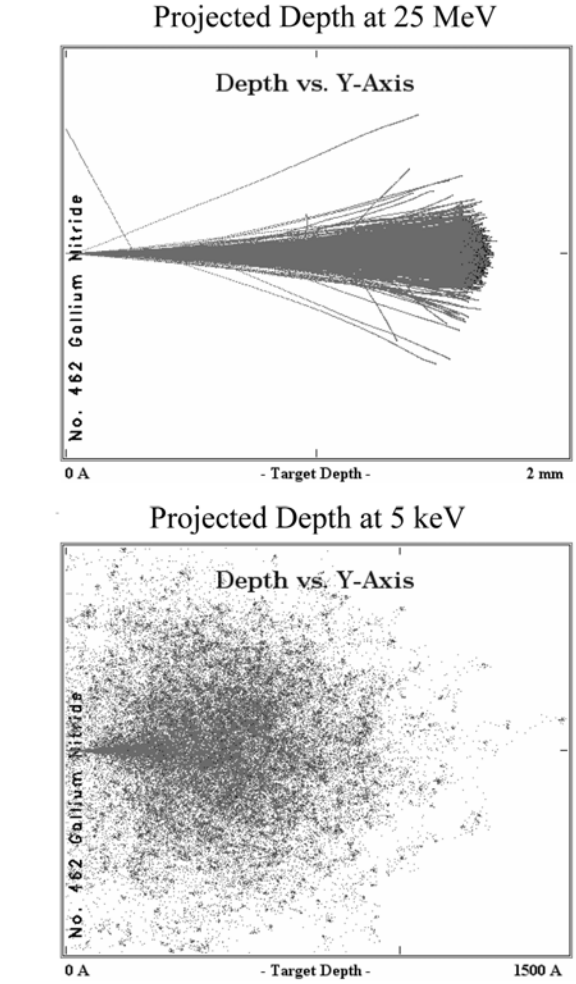

Fig. 3. Projected Depth at 25 MeV, Projected Depth at 5 keV.

between source and drain decreased after proton irradiation due to the creation of defects. I_{DS}-V_{DS} decreased more following 5 keV energy irradiation than following 25 MeV energy irradiaiton. Also, the damage was more severe at higher fluencies. For space missions in the Van Allen belts of earth orbit(exposure to up to several MeV proton energies), AlGaN/GaN HEMT will experience less damage than conventional Silicon and GaAs devices. Therefore AlGaN/GaN is an excellent candidate for space missions where devices face high energy proton irradiation.

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