Energy-Dependent Degradation Characteristics of AlGaN/GaN MISHEMTs with 1, 1.5, and 2 MeV Proton Irradiation

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We investigated the degradation characteristics of AlGaN/GaN metal-Insulator-semiconductor high electron mobility transistors (MISHEMTs) and Schottky HEMTs induced by proton irradiation at energy levels of 1, 1.5, and 2 MeV, with a total fluence of \(5 \times 10^{14} \text{ cm}^{-2}\). Irradiated devices exhibited degradation characteristics of positive threshold voltage \(V_{th}\) shift and drain current \(I_D\) reduction, which increased as the proton energies decreased. Hall pattern measurements revealed that the Hall mobility \(\mu_H\), sheet carrier concentration \(n_{sh}\), and sheet resistance \(R_{sh}\) of the electron channel were also degraded after proton irradiation (showing the same energy dependence). This effect can be attributed to the energy-dependent energy loss of protons penetrating the semiconductor material. Protons with lower irradiation energy can degrade the device characteristics more severely because of the larger amount of nonionizing energy loss (NIEL) in the active region, in which a two-dimensional electron gas (2-DEG) is formed as compared to higher irradiation energies where the energy loss is primarily in the bulk substrate. The capacitance-voltage (C-V) measurements indicated significant degradation of the insulator interface for 1-MeV irradiation.

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Energy-dependent degradation characteristics of AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated remarkable performance improvements in the fields of electronic power and RF applications. These transistors are also promising in the aerospace industry, such as in artificial satellites and weather forecasting, which require strong radiation hardness.1–6 Resistance to proton irradiation is required in space exploration because cosmic rays and solar particle events release significant fluxes of highly energetic protons. Protons are abundant in the low earth orbit, where majority of satellites and spacecraft operate. Proton energies range from hundreds of keV to several thousand MeV.7,8 GaN HEMTs have demonstrated radiation hardness with degradation dependence on the proton-irradiation energy range from 5 to 15 MeV.9–12 In these experiments, the device parameters such as drain current \(I_D\) and transconductance were further reduced as irradiation energy decreased. The authors suggested that proton irradiation with low energy induced displacement damage more effectively near the two-dimensional electron gas (2-DEG) channel because the penetration depth was close to the active layers. In the epitaxial structure considered in this work, the 2-DEG channel at the AlGaN/GaN heterojunction is located approximately 30 nm from the surface. The stopping and range of ions in matter (SRIM)102 calculation showed that the penetration depth \(R_p\) of 5 MeV protons is approximately 104 \(\mu\text{m}\), which is far from the 2-DEG. Therefore, we performed proton irradiation experiments at low energy (i.e., less than 5 MeV) to investigate the energy dependence of degradation with \(R_p\) closer to the 2-DEG channel. AlGaN/GaN metal-insulator-semiconductor high electron mobility transistor (MISHEMT) and Schottky HEMTs were subjected to 1, 1.5, and 2 MeV protons at a fixed fluence of \(5 \times 10^{14} \text{ cm}^{-2}\). We analyzed current-voltage (I-V) characteristics, capacitance-voltage (C-V) characteristics, and 2-DEG channel parameters based on Hall pattern measurements.

**Experimental**

AlGaN/GaN MISHEMTs and Schottky HEMTs were fabricated at the Inter-university Semiconductor Research Center (ISRSC). The AlGaN/GaN-on-Si substrate consisted of a 10-nm in-situ SiNX passivation layer, a 4-nm GaN cap layer, a 24-nm AlGaN barrier layer, a 514-nm i-GaN layer, and a 4.4-\(\mu\text{m}\) GaN buffer layer. First, ohmic contact regions were partially recessed using inductively coupled plasma-reactive ion etching (ICP-RIE) with \(\text{Cl}_2/\text{BCl}_3\) plasma prior to the deposition of a Ti/Al/Ni/Au (=20/120/25/50 nm) metal stack that was alloyed using rapid thermal annealing (RTA) at 830°C for 30 s in N₂ ambient. The active region was defined by mesa formation using \(\text{Cl}_2/\text{BCl}_3\)-based ICP-RIE. A 20-nm SiNX film was deposited as a gate dielectric layer on the MISHEMTs and a passivation layer on the HEMTs using ICP-chemical vapor deposition (ICP-CVD). The RTA process was carried out at 500°C for 5 min in N₂ ambient to improve the properties of the insulators and their interfaces.15 SF₆-based ICP-RIE was used to define a Schottky-gate footprint through the SiNX film for Schottky HEMTs. The gate contact and pad electrodes were simultaneously formed using Ni/Au (=20/200 nm) evaporation. Fig. 1 shows the schematic cross-sectional diagram of the fabricated AlGaN/GaN MISHEMTs on a Si substrate. The tested devices have a gate-to-source distance of 3 \(\mu\text{m}\), a gate length of 2 \(\mu\text{m}\), a gate width of 100 \(\mu\text{m}\), and a gate-to-drain distance of 15 \(\mu\text{m}\).

Proton irradiation tests were performed at energies of 1, 1.5, and 2 MeV using the SSDH-2 Pelletron accelerator at the Korea Multi-purpose Accelerator Complex (KOMAC). A high total fluence of \(5 \times 10^{14} \text{ cm}^{-2}\) was chosen to ensure device degradation. The I-V and C-V characteristics were measured using Agilent 4155A and 1500A parameter analyzers, respectively. The van der Pauw method was applied to the Hall structures to measure \(\mu\), \(n_{sh}\), and \(R_{sh}\) before and after proton irradiation.

**Figure 1.** The schematic cross-sectional diagram of the fabricated AlGaN/GaN MISHEMTs on a Si substrate.
Results and Discussion

When energetic protons are incident on the semiconductor materials, $R_p$ increases with increasing proton energy. The maximum loss of incident proton energy occurs in the vicinity of $R_p$, where severe damage occurs in the semiconductor crystal. As the damaged region moves farther from the active layer with increasing energy and $R_p$, device degradation is alleviated. In our AlGaN/GaN heterostructure, the 2-DEG channel and the GaN-buffer/Si-substrate interface reside at approximately 30 nm and 5 μm from the surface, respectively.

An SRIM simulation was performed to calculate the energy loss of the protons and analyze the lattice damage in the layer structure shown in Fig. 1 with varying incident beam energies; the calculation results are shown in Fig. 2. The $R_p$ values of the protons are 8.8, 15.7, 24.2, and 104 μm for 1, 1.5, 2, and 5 MeV, respectively, which are much deeper than the buffer/substrate interface. The inset in Fig. 2 shows that the energy loss of incident protons within 5 μm from the surface increases when the energy decreases from 5 to 1 MeV. As mentioned in the introduction, the degradation was more pronounced as proton energy decreased from 15 to 5 MeV. It is worthwhile to investigate the energy dependence of degradation below 5 MeV because the damage induced by proton irradiation will be located closer to the 2-DEG channel. Therefore, we chose the proton energies of irradiation tests with $R_p$ that are closer to the active layer than that of 5 MeV to investigate the energy dependence of irradiation damage.

Fig. 3 shows the transfer characteristics of AlGaN/GaN MISHEMTs irradiated with 1, 1.5, and 2 MeV protons. The irradiation-induced degradation becomes worse as beam energy decreases. For 1, 1.5, and 2 MeV, threshold voltage ($V_{th}$) was shifted by 2.68, 1.62, and 1.1 V, and $I_D$ measured at $V_G = 0$ V was reduced by 39.9, 35.8, and 26.5%, respectively. The degradation of the gate leakage characteristics was negligible. The transfer characteristics of AlGaN/GaN Schottky HEMTs exposed to 1-MeV protons are shown in Fig. 4. Schottky HEMTs exhibited the most severe degradation for 1 MeV irradiation. The same energy dependence that was observed with MISHEMTs was observed in the transfer characteristics of Schottky HEMTs. The energy-dependent changes of device parameters after irradiation with 1, 1.5, and 2 MeV protons are summarized in Table I. Fig. 5 shows the output characteristics of AlGaN/GaN MISHEMTs before and after proton irradiation at 1 MeV. The output characteristics of both devices also indicated the same energy dependence as the transfer characteristics. Previous studies have reported that the primary mechanism of proton-induced degradation is displacement damage.15,16 When incident particles collide with lattice atoms, the knocked-on atoms can be displaced from the lattice and generate defects or traps in the semiconductor crystal, which result in degradation of device parameters. The nonionizing energy loss (NIEL), which is the energy loss due to non-ionizing events per unit length (MeV·cm or MeV·cm²/g), is shown in Fig. 6. NIEL has been widely used to quantify the displacement damage. The inset in Fig. 6 shows that the NIEL of incident protons within 5 μm from the surface decreases over the energy range from 1 to 2 MeV. Displacement damage dose (DDD), which is a useful concept for analyzing device degradation due to particle irradiation, can be calculated as the product of NIEL.
and fluence. At lower irradiation energies, DDD increases, because NIEL increases.4,17

To investigate the irradiation effects on 2-DEG channel properties, the Hall mobility (μ), sheet carrier concentration (nsh), and sheet resistance (Rsh) were extracted from the Hall pattern measurements. Fig. 7 clearly shows the energy-dependent degradation of μ, nsh, and Rsh. The μ, nsh, and Rsh values of the 2-DEG channel were degraded from 1890 to 1070 cm²/V·s, from 8.85 × 10¹² to 7.07 × 10¹² cm⁻², and from 377 to 823 Ω/□, respectively, because of proton irradiation at 1 MeV. The Vth shift and the ID reduction in I-V characteristics can be explained by the reduction of nsh and the increase of Rsh in the 2-DEG channel.

Fig. 8 shows the recovery characteristics of AlGaN/GaN MISHEMTs and Schottky HEMTs for RTA treatment at 400 °C for 10 min in vacuum ambient. Vth and ID recovered by 1.98 V and 45.2% for MISHEMTs and 0.65 V and 40% for Schottky HEMTs, respectively. Hall measurement also revealed that μ, nsh, and Rsh recovered partially, from 1070 to 1490 cm²/V·s, from 7.07 × 10¹² to 7.99 × 10¹² cm⁻², and from 823 to 525 Ω/□, respectively, for the sample irradiated with 1-MeV protons. Partial recovery of these parameters can be attributed to the rearrangement of displaced atoms via thermal annealing. Therefore, the degradation of 2-DEG parameters can be attributed to the displacement damage induced by proton irradiation.18,19

The C-V characteristics of AlGaN/GaN MISHEMTs and Schottky HEMTs before and after irradiation with 1-MeV protons were measured at 10 kHz and 1 MHz. Fig. 9 clearly shows a positive shift of the C-V graph caused by a reduction in the channel electron concentration after proton irradiation. This result is consistent with the reduction in nsh observed from Hall measurements. In addition, the frequency dispersion between two frequencies was more pronounced in the MISHEMT structure. The amount of frequency dispersion between low and high frequencies was increased from 0.25 to 0.85 V in AlGaN/GaN MISHEMTs and from 0.15 to 0.45 V in Schottky HEMTs. Frequency dispersion of III-V devices originated from a disordered and defective interfacial layer and the bulk oxide trap of the insulator.20,21 Therefore, the increased frequency-dispersion indicates that the displacement damage due to proton irradiation worsened the properties of the interface between the insulator and the semiconductor. The increase in frequency dispersion in AlGaN/GaN MISHEMTs after proton irradiation was twice as large as that in Schottky HEMTs, suggesting that the interface between SiNX insulator with GaN was severely deteriorated. In our previous experiments with 5-MeV irradiation, the degradation of frequency dispersion in the C-V characteristics was negligible.22 On the contrary, proton irradiation at 1 MeV degraded the MIS interface because the NIEL near the interface for 1-MeV irradiation is larger than that for 5-MeV irradiation. We observed the recovery of C-V characteristics, including a shift in Vth and a reduction in frequency dispersion after RTA treatment.

Table 1. Energy-dependent changes of device parameters after proton irradiation.

| Gate Type | MIS | Schottky |
|-----------|-----|---------|
| Energy (MeV) | 1 | 1.5 | 2 | 1 | 1.5 | 2 |
| ΔVth (V) | 2.68 | 1.62 | 1.1 | 1.33 | 0.85 | 0.72 |
| ΔID (%) | 39.9 | 35.8 | 26.5 | 55.4 | 41.5 | 39.7 |

Figure 4. The transfer characteristics of AlGaN/GaN Schottky HEMTs before and after 1 MeV proton irradiation. VD = 10 V.

Figure 5. The output characteristics of AlGaN/GaN MISHEMTs before and after 1 MeV proton irradiation. VG = 0 V.

Figure 6. NIEL as a function of the target depth derived from SRIM data. (inset) NIEL within the GaN buffer layer.

Figure 7. Energy dependence of μ, nsh, and Rsh in the 2-DEG channel extracted from Hall pattern measurements.
Figure 8. The recovery characteristics of 1 MeV-irradiated device after RTA treatment at 400°C for 10 min in vacuum ambient. (a) MISHEMTs and (b) Schottky HEMTs.

Summary

We investigated the degradation characteristics of AlGaN/GaN MISHEMTs and Schottky HEMTs irradiated with 1, 1.5, and 2 MeV protons. Both devices showed a positive shift of $V_{th}$ and a reduction of $I_D$. The devices exhibited the largest degradation when they were irradiated with 1-MeV protons. Hall pattern measurements revealed that the transport properties of the 2-DEG channel were degraded based on energy dependence, as was observed in the I-V characteristics. The degradation induced by displacement damage was partially recovered via atom relocation after annealing treatment. Unlike the case of Schottky HEMTs, the degradation of the MIS interface in MISHEMTs was also observed in the C-V measurements after 1-MeV irradiation, suggesting that the metal-semiconductor interface is more robust to proton radiation than the MIS interface. The energy dependence of degradation characteristics should be linked to the larger NIEL near the surface and active layer for lower irradiation energies, compared to that of higher irradiation energies.

Acknowledgments

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References

1. R. S. Pengelly, S. M. Wood, J. W. Milligan, S. T. Sheppard, and W. L. Pribble, *IEEE Trans. Microw. Theory Tech.*, 60, 1764 (2012).
2. K. J. Chen, O. Haberlen, A. Lidow, C. L. Tsai, T. Ueda, Y. Uemoto, and Y. Wu, *IEEE Trans. Electron Devices*, 64, 779 (2017).
3. J. Muraro, G. Nicolas, D. M. Ntut, S. Forestier, S. Rochette, O. Vendier, D. Langrez, J. Cazaux, and M. Froude, *Int. J. Microw. Wireless Technol.*, 2, 121 (2010).
4. S. J. Pearton, F. Ren, E. Patrick, M. E. Law, and A. Y. Polyakov, *ECS J. Solid State Sci. Technol.*, 5, Q35 (2016).
5. J. Kim, K. Choi, S. Lee, H. Park, and Y. Kwon, *J. Electromagn. Eng. Sci.*, 16, 44 (2016).
6. D. H. Shin, I. B. Yom, and D. W. Kim, *J. Electromagn. Eng. Sci.*, 17, 178 (2017).
7. W. Suparta and S. K. Zulkifli, *J. Phys. Conf. Ser.*, 495 012040 (2014).
8. O. Zeynali, D. Masti, A. Ebrahimi, M. Orvatinia, and N. Maryam, *Elec. Electron. Eng.*, 1, 112 (2011).
9. H.-Y. Kim, J. Kim, L. Liu, C.-F. Lo, F. Ren, and S. J. Pearton, *J. Vac. Sci. Tech B*, 30, 012202 (2012).
10. C.-F. Lo, L. Liu, F. Ren, S. J. Pearton, B. P. Gila, H.-Y. Kim, J. Kim, O. Laboutin, Y. Cao, I. W. Johnson, and I. I. Kravchenko, *J. Vac. Sci. Tech. B*, 30, 041206 (2012).
11. L. Liu, C.-F. Lo, Y. Xi, Y. Wang, F. Ren, S. J. Pearton, H.-Y. Kim, J. Kim, R. C. Finch, D. E. Walker Jr., K. D. Chabak, J. K. Gillespie, S. E. Tetlak, G. D. Via, A. Crespo, and I. I. Kravchenko, *J. Vac. Sci. Tech. B*, 31, 022201 (2013).
12. S. Amin, C. Dong, W. Zhu, B. J. Kim, Y. H. Hwang, F. Ren, S. J. Pearton, G. Yang, J. Kim, E. Patrick, B. Tracy, D. J. Smith, and I. I. Kravchenko, *J. Vac. Sci. Tech. B*, 33, 051208 (2015).
13. http://www.srim.org/.
14. M. T. Hasan, T. Kojima, H. Tokuda, and M. Kozuhara, in *2013 International Conference on Compound Semiconductor Manufacturing Technology*, pp. 131 (2013).

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15. N. E. Ives, J. Chen, A. F. Witulski, R. D. Schrimpf, D. M. Fleetwood, R. W. Bruce, M. W. McCurdy, E. X. Zhang, and L. W. Massengill, *IEEE Trans. Nucl. Sci.*, 62, 2417 (2015).

16. B. D. Weaver, P. A. Martin, J. B. Boos, and C. D. Cress, *IEEE Trans. Nucl. Sci.*, 59, 3077 (2012).

17. S. R. Messenger, E. A. Burke, G. P. Summers, M. A. Xapsos, R. J. Walters, E. M. Jackson, and B. D. Weaver, *IEEE Trans. Nucl. Sci.*, 46, 1595 (1999).

18. D. M. Keum, H.-K. Sung, and H. Kim, *IEEE Trans. Nucl. Sci.*, 64, 258 (2017).

19. B.-J. Kim, S. Ahn, F. Ren, S. J. Pearton, G. Yang, and J. Kim, *J. Vac. Sci. Technol. B*, 34, 041231 (2016).

20. R. V. Galatage, D. M. Zhernokletov, H. Dong, B. Brennan, C. L. Hinkle, R. M. Wallace, and E. M. Vogel, *J. Appl. Phys.*, 116, 014504 (2014).

21. Y. Yuan, B. Yu, J. Ahn, P. C. McIntyre, P. M. Asbeck, M. J. W. Rodwell, and Y. Taur, *IEEE Trans. Electron Devices*, 59, 2100 (2012).

22. D. M. Keum, H.-Y. Cha, and H. Kim, *IEEE Trans. Nucl. Sci.*, 62, 3362 (2015).