phys. stat. sol. (c) **3**, No. 6, 2338–2341 (2006) / **DOI** 10.1002/pssc.200565304

High and low energy proton irradiation effects on AlGaN/GaN HFETs

G. Sonia*, [1], E. Richter[1], R. Lossy[1], M. Mai[1], J. Schmidt[1], M. Weyers[1], G. Tränkle[1], A. Denker[2], J. Opitz-Coutureau[2], G. Pensl[3], I. Brauer[4], and **H. P. Strunk[4]**

[1] Ferdinand-Braun-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Straße 4, 12489 Berlin, Germany
[2] Ionenstrahllabor, Hahn-Meitner-Institut, Glienicker Straße 100, 14109 Berlin, Germany
[3] Institut für Angewandte Physik, Universität Erlangen-Nürnberg, Staudtstraße 7, 91058 Erlangen, Germany
[4] Institut für Werkstoffwissenschaften VII, Universität Erlangen-Nürnberg, Cauerstraße 6, 91058 Erlangen, Germany

Received 9 August 2005, accepted 23 December 2005
Published online 15 May 2006

PACS 61.82.Fk, 73.61.Ey, 85.30.Tv

AlGaN/GaN heterojunction field effect transistors (HFETs) have been irradiated with protons at 68 MeV and 2 MeV with fluences up to 10^{13} cm^{-2} in order to simulate operation in space. Hall effect measurements, dc characteristics and RF load pull measurements at 2 GHz do not reveal significant changes indicating the suitability of the transistors for reliable operation in space.

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

Gallium nitride-based heterojunction field effect transistors (HFETs) have attracted much interest for high-power applications at microwave frequencies [1]. The electrical properties of GaN-based devices i.e the ability to handle high power and high frequencies make these devices suitable for broadband communication systems. GaN-based devices also have the potential to exhibit extremely high radiation hardness [2]. Systems employing GaN devices are designed for use in space, where they are exposed to both particle bombardment and electromagnetic radiation. Therefore it is important to understand the radiation tolerance of GaN electronic devices. Inside the earth magnetosphere there are two Van Allen regions [3] of trapped fast particles, mostly electrons and protons. As a consequence a satellite located at any orbit will be exposed to a flux of high energy particles.
Cai et al. reported a decrease in dc saturation current (I_{DS}) and transconductance (g_m) after irradiation with 1.8 MeV protons at a fluence of 10^{14} cm^{-2} [4]. For 40 MeV and a fluence of $5x10^{10}$ cm^{-2} Luo and co-workers reported decreases in I_{DS} of 20% and in g_m of 30% [5]. Subsequent work on passivated devices irradiated at 40 MeV and a fluence of $5x10^{9}$ cm^{-2} revealed only small changes [6]. To test the response to proton irradiation induced damage in our AlGaN/GaN HFETs, this paper describes the results of 68 MeV and 2 MeV proton irradiation on a series of devices from the same wafer. The fluences were between 10^{10} and 10^{13} cm^{-2} with the later value corresponding to 10–100 years operation in space.

* Corresponding author: e-mail: gnanapragasam@fbh-berlin.de, Phone: +49 030 6392 2688, Fax: +49 030 6392 2685

WILEY InterScience® DISCOVER SOMETHING GREAT

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

2 Experimental

The GaN HFETs used in the present investigation were processed from epitaxial structures grown by Metal Organic Vapour Phase Epitaxy (MOVPE) and consisted of 2.7 µm of unintentionally doped GaN grown on c-plane sapphire substrate, followed by 3 nm spacer layer, 12 nm supply layer, 10 nm barrier layer with $Al_{0.25}Ga_{0.75}N$ and a GaN cap of 5 nm. The AlGaN supply layer was doped with Si to a carrier concentration of $5x10^{18}$ cm^{-3}. Further fabrication comprises device isolation by dry etching, drain and source ohmic contacts (Ti/Al/Ti/Au: 110 nm), rectifying Schottky contacts for the gate electrode (Pt/Ti/Au: 550 nm), surface passivation with PECVD - SiNx and deposition of metal pads.
The gate length and width are 1.8 µm and 250 µm. Devices were diced and the chips were irradiated at room temperature with protons at 68 MeV and 2 MeV with fluences of 10^{10}, 10^{11}, 10^{12} and 10^{13} cm^{-2}. The penetration depth for GaN as calculated by Monte Carlo simulation SRIM was 9 mm for 68 MeV and 24 µm for 2 MeV protons. Penetration depths in Au are 42 µm for 68 MeV and 15 µm for 2 MeV. These values were calculated since some parts of the devices were covered with 6 µm Au plating. The active part of the device i.e the gate region is not capped with Au plating. The SRIM calculation shows that the protons pass through the plating for both energies. Before and after irradiation the electrical parameters were studied at room temperature by dc characterization i.e output and transfer characteristics measured with an automatic wafer prober. Pulsed I-V characteristics were measured by Dynamic I-V Analyser (DIVA) using Accent D625. Additionally, Hall measurements were performed at room temperature on test structures. To study the structural effects of the proton bombardment selected samples were analysed by cross-section TEM.

3 Results and discussion

Hall effect measurements for unirradiated control devices showed an electron mobility of 1350 cm^2/Vs and sheet carrier concentration of 7.3 x 10^{12} cm^{-2} at room temperature. No significant changes in mobility and sheet carrier concentration were observed after proton irradiation for fluences up to 10^{13} cm^{-2}. Similarly, no remarkable differences were observed in the dc output characteristics after irradiation. For devices irradiated with 68 MeV the I_{DS} vs. V_{DS} curves nearly coincide, for 2 MeV the maximum I_{DS} value is slightly increased by about 5 % for the highest fluence of 10^{13} cm^{-2}. Since the observed effects are only small we will concentrate on this highest fluence in the following. The transfer characteristics of a HFET before and after irradiation are shown in Fig. 1. In Fig. 1(a), no changes even for the highest fluence of 10^{13} cm^{-2} were observed before and after 68 MeV irradiation as can be seen from the coincident g_m dependencies. The peak transconductance g_m before and after irradiation was 106 mS/mm at V_{GS} = -2.24 and V_{DS} = 15 V. In contrast in Fig. 1(b), although the maximum g_m remains unchanged before and after 2 MeV irradiation, e.g. 100 mS/mm at V_{GS} = -1.97 and V_{DS} = 15 V for a fluence of 10^{13} cm^{-2}, a small broadening of the g_m characteristic was observed. The breakdown voltage V_{Br} for all fluences did not change due to irradiation.

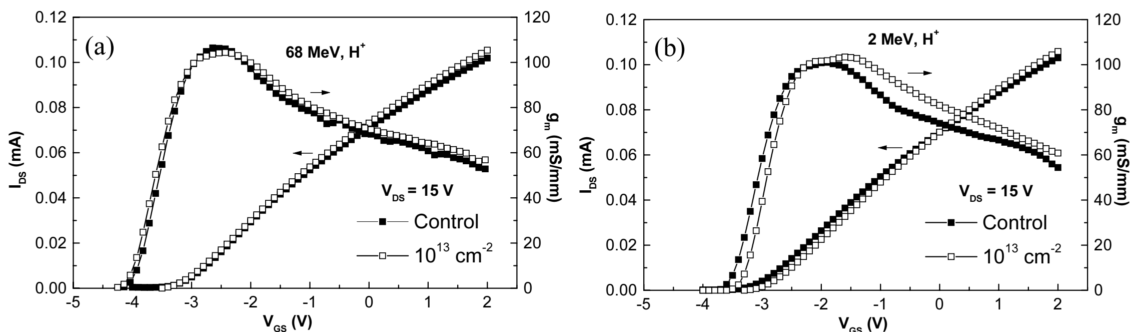

Fig. 1 Transfer characteristics for AlGaN/GaN HFETs before and after proton irradiation at (a) 68 MeV and (b) 2 MeV at a fluence of 10^{13} cm^{-2}.

 © 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

In the pulsed I-V measurements the gate and drain voltage are pulsed away from the steady state bias for 200 ns at 2 kHz repetition rate. Trapped carriers cannot follow these fast changes and are frozen at the biasing conditions. Two conditions have been used, (i) represents the standard unbiased case V_{DS} = 0.0V, V_{GS} = 0.0 V and condition (ii) V_{DS} = 20.0 V, V_{GS} = -3.50 V is sensitive to the traps causing drain lag [7]. Table 1 tabulates the obtained results. For the control sample I_{DS} under condition (ii) is about 20% lower than under condition (i) indicating the presence of traps before irradiation. The difference between (i) and (ii) is reduced to 6% at 2 MeV and 12 % at 68 MeV indicating that irradiation has not induced additional traps in the bulk responsible for drain lag. On the contrary, the density of these traps seems to be higher in the control sample. In summary, no significant degradation of the device characteristics can be concluded from the pulsed I-V measurements.

Table 1 Pulsed dc values for the two conditions (i) V_{DS} = 0.0 V, V_{GS} = 0.0 V and (ii) V_{DS} = 20.0 V, V_{GS} = -3.50 V.

At V_{DS} = 10 V, V_{GS} = -1.0 V	(i) No bias, I_{DS} (mA)	(ii) Bias, I_{DS} (mA)	Difference %
Unirradiated Control	109	87	-19
2 MeV, 10^{13}cm^{-2}	87	78	-6
68 MeV, 10^{13}cm^{-2}	82	71	-12

Figures 2(a) and (b) show the load pull measurement for AlGaN/GaN HFETs before and after irradiation. Large signal on wafer microwave measurements were made at 2 GHz using a passive load pull systems in class A operation with a dc bias of: V_{DS} = 20 V, V_{GS} = - 0.5 V. The calculated power density for these devices was 1.5 W/mm. The P_{out}, PAE and gain were unchanged due to irradiation.

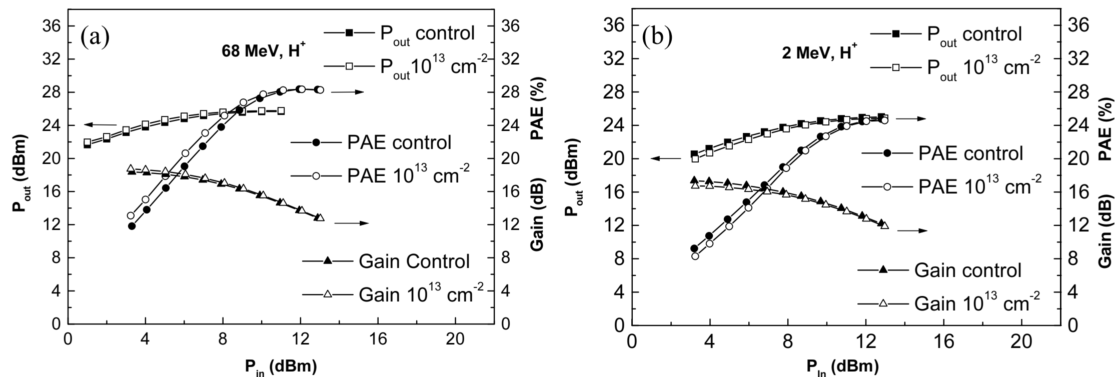

Fig. 2 Load pull measurements for AlGaN/GaN HFETs before and after proton irradiation at (a) 68 MeV and (b) 2 MeV at a fluence of 10^{13} cm^{-2}.

Cross sectional TEM samples of the active gate region were prepared by means of focussed ion beam etching. Figure 3(a) shows the gate region of a control sample. After 68 MeV proton irradiation the gate metallization is slightly distorted (Fig. 3b). For 2 MeV irradiation (Fig. 3c) this distortion is even more pronounced. From the above pictures it can be concluded that 2 MeV protons cause some changes in the gate region. However, as seen in Figs. 2(a) and (b) this distortion does not change the device performance significantly. For 2 MeV the penetration depth is lower and hence the number of protons deposited in the gate region is higher than for 68 MeV. Apparently, proton diffusion results in a roughening of the gate metal interfaces and as a consequence slightly deteriorated device performance at 2 MeV (broadening of g_m peak) is observed. No extended defects were observed for both energies in the TEM analysis.

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

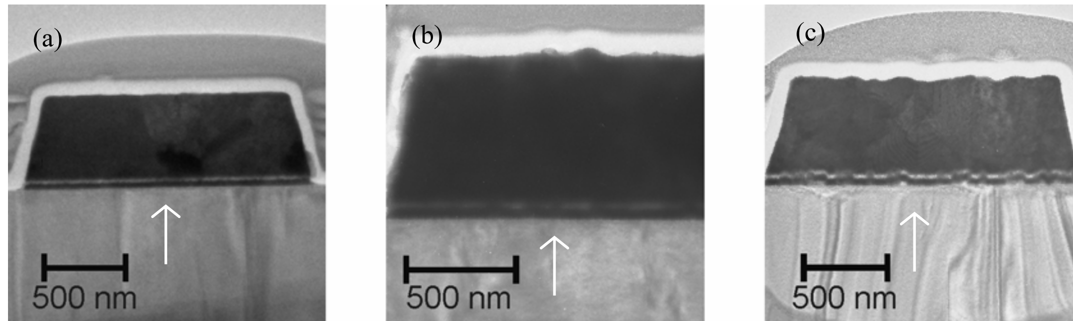

Fig. 3 Cross sectional TEM micrographs of (a) control sample and after proton irradiation at (b) 68 MeV and (c) 2 MeV at a fluence of 10^{13} cm^{-2}.

4 Conclusions

The effects of proton irradiation at 68 and 2 MeV on AlGaN/GaN HFETs were studied. No significant degradation was observed in dc saturation current (I_{DS}), PAE and gain after proton irradiation up to fluences of 10^{13}cm^{-2}. Only g_m is slightly affected by 2 MeV irradiation. At this energy also a roughening of the gate metallization is observed. Despite the small changes found devices are reliable since the fluence of 10^{13} cm^{-2} simulates more than 10 years of operation in space. Hence AlGaN/GaN HFETs appear to be excellent candidates with respect to the expected proton bombardment for space missions in the earth orbit.

Acknowledgements One of the authors G. S. acknowledges the DAAD Leibniz organisation for the fellowship offered to carry out this work in Germany. I. B. acknowledges financial support by Prof. G. Mueller, Intstitute of Material Science VI, University Erlangen-Nuernberg. We thank Ms. S. Petersen, (Fraunhofer Institute of Integrated Systems and Device Technology) for FIB preparation**.**

References

[1] C. Nguyen, N. X. Nguyen, and D. E Grider, Electron. Lett. **35**, 1380 (1999).
[2] A. Ionascut-Nedelcescu, C. Carlone, A. Houdayer, H. J. von Bardeleben, J. L. Cantin, and S. Raymond, IEEE Trans. Nucl. Sci. **49**, 2733 (2002).
[3] E. G. Stassinopoulos and J. P. Raymond, Proc. IEEE **76**, 1423 (1988).
[4] S. J. Cai, Y. S. Tang, R. Li, Y. Wei, L. Wong, Y. L Chen, K. L Wang, M. Chen, Y. F. Zhao, R. D. Schrimpf, J. C. Keay, and K. F. Galloway, IEEE Trans. Electron Devices **47**, 304 (2000).
[5] B. Luo, J. W. Johnson, F. Ren, K. K. Allums, C. R. Abernathy, S. J. Pearton, R. Dwivedi, T. N. Fogarty, R. Willams, A. M. Dabiran, A. M. Wowchack, C. J. Polley, P. P. Chow, and A. G. Baca, Appl. Phys. Lett. **79**, 2196 (2001).
[6] B. Luo, J. J. Kim, F. Ren, J. K. Gillespie, R. C. Fitch, J. Sewell, R. Dettmer, G. D Via, A. Crespo, T. J. Jenkins, B. P. Gila, A. H. Onstine, K. K. Alums, C. R. Abernathy, S. J. Pearton, R. Dwivedi, T. N. Fogarty, and R. Wilkins, Appl. Phys. Lett. **82**, 1428 (2003).
[7] S. C. Binari, K. Ikossi, J. A. Roussos, W. Kruppa, D. Park, H. B. Dietrich, D. D. Koleske, A. E. Wickenden, and R. L. Henry, IEEE Trans. Electron Devices **48**, 465 (2001).

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim