High and Low Energy Irradiation Effects on AlGaN/GaN HFET Devices and Thick GaN layer

S. Gnanapragasam\textsuperscript{1,5}, E. Richter\textsuperscript{1}, F. Brunner\textsuperscript{1}, A. Denker\textsuperscript{2}, R. Lossy\textsuperscript{1}, M. Mai\textsuperscript{1}, F. Lenk\textsuperscript{1}, J. Opitz-Coutureau\textsuperscript{2}, J. Bundesmann\textsuperscript{2}, G. Pensl\textsuperscript{3}, J. Schmidt\textsuperscript{1}, U. Zeimer\textsuperscript{1}, L. Wang\textsuperscript{1}, M. Herms\textsuperscript{1}, C. Cobet\textsuperscript{4}, N. Esser\textsuperscript{4}, K. Baskar\textsuperscript{5}, M. Weyers\textsuperscript{1}, J. Würfl\textsuperscript{1}, and G. Tränkle\textsuperscript{1}

\textsuperscript{1}Ferdinand-Braun-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany
\textsuperscript{2}Ionenstrahlabor, Hahn-Meitner-Institut, Glienicker Str. 100, 14109 Berlin, Germany
\textsuperscript{3}Institut fuer Angewandte Physik, University Erlangen-Nuernberg, 91058 Erlangen, Germany
\textsuperscript{4}Institute for Analytical Sciences, Albert-Einstein-Str. 9, 12489 Berlin, Germany
\textsuperscript{5}Crystal Growth Centre, Anna University, Chennai-600 025, India

For microwave power amplification in satellite links and wireless communication applications, the AlGaN/GaN transistors has emerged as the most promising device. The potential applications for HFETs are in broad-band satellite transmission for communication, television, and weather forecasting systems which will operate in low earth orbit, therefore it is necessary for these devices to be radiation resistant [1]. The choice of the species for our irradiation experiments is dictated by the fact that the space environment consists of 85% protons, 14% alpha particles (decay product of helium from solar flares) and 1% heavy ions (originating from galactic cosmic ray and solar flares) [2].

High energy irradiation experiments were performed at 68 MeV for proton, carbon, oxygen and 120 MeV for krypton. The fluences for proton were in the range of $1 \times 10^{10}$ to $1 \times 10^{13}$ cm$^{-2}$ while for carbon, oxygen and krypton they were in the range of $1 \times 10^{7}$ to $1 \times 10^{10}$ cm$^{-2}$. In parallel thick GaN layer samples were also irradiated, always at the highest fluence, for the investigation of radiation induced defects in GaN. The DC characteristics of the transistors showed no remarkable changes after irradiation with protons [3] and heavy ions such as carbon and oxygen. Other parameters such as the contact and sheet resistance, threshold voltage, gate leakage current and breakdown voltage also showed no changes after high energy irradiation for all fluences and ion types. Only for krypton at the highest fluence of $1 \times 10^{10}$ cm$^{-2}$ there was a small decrease of about 2% in output and transfer characteristics. Pulsed I-V characteristics showed results analogous to that of the DC characteristics. There were no significant changes for all ions and fluences. Similarly no changes were exhibited in loadpull parameters like the output power ($P_{\text{out}}$), PAE and gain. The S-parameters such as $f_{\text{T}}$ and $f_{\text{max}}$ also did not show any changes after irradiation. This indicates that the GaN-based devices well tolerate the high energy irradiation, however some shielding is needed against high mass heavy ions like for instance krypton. The results of the measurements on device and thick GaN samples were explained with SRIM simulation. The penetration depth of proton, carbon, oxygen and krypton are far beyond the actual device thickness which indicates that the highly energetic ions just pass through the device and thick GaN layer without exchanging too much energy.

The results obtained on devices were correlated with those obtained from the thick GaN layer since this comparison could help in understanding the effects of high energy irradiation on the different device components. High energy irradiation with protons, carbon and oxygen of thick GaN samples, did not produce significant changes in the XRD, PL and Hall datas. On the other hand, carbon and proton irradiation did change the Raman and ellipsometry results,
in contradiction to the device results. The $E_2^H$ phonon showed an increase in frequency for carbon and a decrease for proton irradiation. The surface roughness increased corresponding to proton and carbon irradiation, which explains the change in the pseudo dielectric function revealed by ellipsometry. Irradiation with krypton showed a change in XRD, PL and Hall measurements. There was a small shift in the peak position of XRD, which ultimately indicated the changes in the lattice constant $a$ and $c$, while the PL intensity was reduced. The GaN layer showed high resistivity as detected by Hall measurement.

The low energy irradiation was performed at 2 MeV with protons, carbon, oxygen, iron and krypton. The fluences for proton were in the range of $1 \times 10^{10}$ to $1 \times 10^{13}$ cm$^{-2}$ while for heavy ions were in the range of $1 \times 10^9$ to $1 \times 10^{12}$ cm$^{-2}$. No remarkable changes were seen in DC characteristics, pulsed characteristics, loadpull and S-parameter of our transistors after proton irradiation but remarkable changes were observed after irradiation with carbon, oxygen, iron and krypton at the highest fluence of $1 \times 10^{12}$ cm$^{-2}$. For oxygen and carbon small changes in the DC characteristics, loadpull and S-parameter measurements appeared already at $5 \times 10^{10}$ cm$^{-2}$. For carbon irradiation at $1 \times 10^{12}$ cm$^{-2}$ the output current ($I_{DS}$), transconductance ($g_m$), loadpull parameters $P_{out}$, PAE and gain as well as S-parameters decreased by about 50%. For oxygen at the same fluence $I_{DS}$ and $g_m$ were reduced by 70%. In the cases of iron and krypton, there was a small degradation of the device characteristics corresponding to fluence of $1 \times 10^9$ cm$^{-2}$. At $5 \times 10^{10}$ cm$^{-2}$ $I_{DS}$ and $g_m$ were reduced by 30% while the devices did not work anymore after irradiation at $1 \times 10^{12}$ cm$^{-2}$. Correspondingly, changes were observed in sheet and contact resistance, mobility and carrier concentration, threshold voltage, gate leakage current and breakdown voltage of the transistors for different ions and fluences. Similarly, changes in pulsed I-V characteristics, loadpull parameters - $P_{out}$, PAE, gain and S-parameters - $f_t$ and $f_{max}$ were significant with heavy ions at different fluences.

The device results were correlated with those obtained from thick GaN samples exposed to the same irradiation processes. No changes in XRD and PL characteristics were observed for proton irradiation at a fluence of $1 \times 10^{13}$ cm$^{-2}$ while changes were observed in Hall, Raman and ellipsometry characteristics. The mobility and carrier concentration could not be measured as the layer became highly resistive. The $E_2^H$ phonon frequency for proton showed a decrease while the dielectric function increased, indicating that the surface roughness was increased. For carbon, oxygen, iron and krypton irradiation the changes of the physical characteristics were significant. At a fluence of $1 \times 10^{12}$ cm$^{-2}$ the XRD investigations showed a change in the lattice constant $a$ and $c$, the PL measurements showed a reduction in PL intensity for carbon and oxygen while quenching of luminescence occurred for iron and krypton. Hall effect measurements revealed a decrease of mobility and carrier concentration whereas Raman measurements showed an increase in $E_2^H$ phonon frequency for krypton. Finally, the effect of low energy irradiation on devices and thick GaN samples were simulated by SRIM. The penetration depth of 2 MeV ions is generally smaller than the active region of the device and the thick GaN layer, i.e. the ions are stopped within the layers. This fact indicates that the heavy ions may exchange a lot of energy with the lattice, thus giving rise to remarkable displacement damage and degradation of the device and GaN layer characteristics.