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Impact of proton irradiation on the dc and rf performance of AlGaN/GaN high electron mobility transistors

L. Liu[1], Y. Y. Xi[1], F. Ren[1], S. J. Pearton[2], H.-Y. Kim[3], J. Kim[3], and I. I. Kravchenko[4]

1. Department of Chemical Engineering, University of Florida, Gainesville, FL 32611
2. Department of Materials Science and Engineering, University of Florida, Gainesville FL 32611
3. Korea University, Seoul 136-701, Korea
4. Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37830

The effects of proton irradiation dose on dc characteristics and the reliability of AlGaN/GaN high electron mobility transistors (HEMTs) were investigated. The HEMTs were irradiated with protons at a fixed energy of 5 MeV and doses ranging from 10^9 to 2×10^{14} cm^{-2}. For the dc characteristics, there was only minimal degradation of saturation drain current (I_{DSS}), transconductance (g_m), electron mobility and sheet carrier concentration at doses below 2×10^{13} cm^{-2}, while the reduction of these parameters were 15%, 9%, 41% and 16.6%, respectively, at a dose of 2×10^{14} cm^{-2}. At this same dose condition, increases of 37% in drain breakdown voltage (V_{BR}) and of 45% in critical voltage (V_{cri}) were observed. The improvement of device reliability was attributed to the modification of the depletion region due to the introduction of a higher density of defects after irradiation at a higher dose.

The AlGaN/GaN HEMT device structures were grown on semi-insulating 6*H*-SiC substrates and consisted of a thin AlN nucleation layer, 2.25 µm of *Fe*-doped GaN buffer, 15 nm of $Al_{0.28}Ga_{0.72}N$, and a 3 nm undoped GaN cap. On-wafer Hall measurements showed sheet carrier concentrations of 1.06×10^{13} cm^{-2}, mobility of 1907 cm^2 /V-s, and sheet resistivity of 310 Ω/□. The HEMTs employed dry etched mesa isolation, Ti/Al/Ni/Au Ohmic contacts alloyed at 850°C (contact resistance of 0.3 Ω•mm), and dual-finger Ni/Au gates patterned by lift-off. The gate length was 1µm, and gate width was 2×150 µm. Both source-to-gate gap and gate-to-drain distances were 2 µm. The devices exhibited typical maximum drain currents of 1.1 A/mm, extrinsic transconductance of 250 mS/mm at V_{DS} of 10 V, threshold voltage of -3.6 V. The devices were passivated with 200 nm of SiN_x deposited by a Plasma Therm 790 PECVD system.

For the dose of 10^9 cm^{-2}, there was no change for all those parameters. The threshold of R_C and R_T degradation was at a proton dose of 5×10^9 cm^{-2}, and the R_C and R_T increased linearly proportional to the proton dose until the proton dose reached at 2×10^{13} cm^{-2}, exhibiting 3 and 5.5% increases for R_T and R_C, respectively. However, the threshold of the proton dose for R_S degradation was much higher at 2×10^{13} cm^{-2} as compared to those for R_T and R_C. There was no degradation for R_S detected for the lower dose protons irradiation, in which the density of irradiation-induced defects was still negligible as compared to the native defect density. For the condition of the highest proton dose of 2×10^{14} cm^{-2} used in this study, R_S, R_C and R_T increased 7.9, 6.7 and 7.5%, respectively. The increase of R_T and R_C under the Ohmic contacts could be due to more defects created by proton irradiation in these disordered regions. It is well known that significant increases of edge- and mixed-type threading dislocations (TDs) are induced by metal contact inclusions after high temperature (>850°C) Ohmic contact annealing.

In contrast to the trends in I_{DSS}, HEMTs irradiated with higher doses of protons exhibited higher drain breakdown voltages, V_{BR}, as illustrated in Table III. Below a threshold dose of 2×10^{13} cm^{-2}, the V_{BR} was fairly constant around 30 ± 1 V. However, the V_{BR} of HEMTs irradiated with higher doses increased by 20% and 37% for the HEMTs irradiated at 2×10^{13} cm^{-2} and 2×10^{14} cm^{-2} protons, respectively. The V_{BR} was highly dependent on the electrical field distribution around gate edges. The electrode electrical field does not evenly distribute around the gate, with the highest electrical fields located at the edges of the gate and field plate used to reduce the peak electrical field on the edges of the gate electrode.

Off-state drain-voltage step-stress was also conducted on AlGaN/GaN HEMTs prior to and after proton irradiation to evaluate device reliability[20]. The HEMTs were constantly biased for 60 s at each drain-voltage step, while grounding the source electrode and fixing the gate voltage at -8V. The stress started at 5 V of drain voltage and drain voltage step was 1 V. To protect devices, a compliance of 50 µA was set during electrical stress. During the step-stress, besides monitoring I_G, gate-to-source leakage current, I_{GS}, and gate-to-drain leakage current, I_{GD}, were also measured. Due to the low drain-to-source current during off-state, self-heating effect was negligible and had no effect on device performance. The critical voltage, V_{cri}, of the off-state step stress was defined as the onset of a sudden I_G increase during the stress. As previous work reported, permanent damage in the devices may be created upon exceeding V_{cri}, including the formation of cracks on both source and drain sides of gate edges, the diffusion of gate metal and native oxide layer at the interface between metal and AlGaN barrier layer, as well as associated threading dislocations, all of which could provide possible leakage paths. These mechanisms also cause the irreversible degradation of dc characteristics of GaN-based HEMTs. There was no difference in V_{cri}, 22 ± 1 V, detected for the pristine and proton-irradiated HEMTs with a dose less than 2×10^{13} cm^{-2}, as shown in Table III. However, larger V_{cri} values of 28 and 32 V were observed for HEMTs irradiated with higher doses of 2×10^{13} and 2×10^{14} cm^{-2}, respectively. The improvement of V_{cri} could be ascribed to the previously described mechanism for the improvement of drain breakdown voltage[6]. A virtual gate was formed in the buffer layer for the proton irradiated HEMTs, which reduced the maximum electric field by extending the depletion region into the buffer layer.

We studied the effects of proton doses on dc characteristics and the reliability of irradiated AlGaN/GaN HEMTs by dc measurement and off-state electrical stress. There were less degradation in saturation drain current (I_{DSS}), transconductance (g_m), mobility and sheet carrier concentration at doses below 2×10^{13} cm^{-2}. As irradiation dose increased, the increase of V_{BR} were 20% and 37%, V_{cri} were 27% and 45% at doses of 2×10^{13} and 2×10^{14} cm^{-2}, respectively. The improvement of device reliability was attributed to the modification of depletion region due to the introduction of a higher density of defects after irradiation at a higher dose.