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INNOVATIVE SOLUTIONS FOR NANOFABRICATION
Effects of 2 MeV Ge$^+$ irradiation on AlGaN/GaN high electron mobility transistors

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The dc characteristics of AlGaN/GaN high electron mobility transistors (HEMTs) were measured before and after irradiation with 2 MeV Ge$^+$ ions at doses from $5 \times 10^{10}$ to $5 \times 10^{12}$ cm$^{-2}$. The drain current, gate leakage current, and transconductance decreased monotonically with dose, while the drain-source resistance increased to a much greater extent than observed previously for proton irradiation of similar devices. The data are consistent with a strong decrease in electron concentration in the HEMT channel. During off-state electrical stressing of AlGaN/GaN HEMTs, the typical critical voltage for unirradiated devices was $\sim$13 V. By sharp contrast, no critical voltage was detected for proton irradiated HEMTs up to 35 V, indicating that the Ge irradiation had a strong influence on the electric field distribution near the gate electrode. © 2013 American Vacuum Society. [http://dx.doi.org/10.1116/1.4792370]

I. INTRODUCTION

The radiation hardness of GaN-based devices is about an order of magnitude higher than for their AlGaAs/GaAs counterparts. This is a consequence of the higher binding energy in GaN leading to a reduced introduction rate of primary radiation defects. For both GaN and the most common heterostructure AlGaN/GaN used in nitride-based high electron mobility transistors (HEMTs), the effects of proton and electron irradiation are reasonably well documented. The carrier removal rate in proton irradiated n-GaN was found to be in the range $10^2$–$10^3$ cm$^{-1}$ depending on the proton energy and was shown to increase for higher donor concentrations. The most prominent defect levels created are deep traps with activation energies of 0.13, 0.16–0.18, 0.2–0.21 eV, while electron irradiation created the 0.16–0.18 eV traps due to N vacancies. For high doses of protons, aggregates of primary defects can be formed and thermally stable electron traps with activation energy 0.75, 0.95 eV were reported. These deep electron traps increase the HEMT channel resistance. Postirradiation annealing at 300 °C is able to restore $\sim$70% of the initial transconductance ($g_m$) and drain-source current ($I_{DS}$) values in HEMTs receiving proton doses of $5 \times 10^{10}$ cm$^{-2}$. However, little is known about the effects of heavier ions. Earth’s magnetosphere is bombarded by a nearly isotropic flux of energetic charged particles comprising $\sim$85% protons, 14% x-particles, and 1% heavier ions covering the full range of elements. In addition, solar flares interacting with the van Allen belts produce protons and heavier ions with energies up to several hundred MeV. In this work, we irradiated AlGaN/GaN HEMTs with 2 MeV Ge$^+$ ions from doses of $5 \times 10^{10}$ to $5 \times 10^{12}$ cm$^{-2}$ and measured the effect on their dc characteristics as well as on their apparent reliability. Previous investigations into the effect of heavy ions on AlGaN/GaN heterostructure field effect transistors, reported by Sonia et al., have indicated a clear dependence of fluence and ion species (e.g., Fe and Kr) on device performance. The degradation of device characteristics did not necessarily follow a linear trend with fluence. Similar results were observed in this study.

II. EXPERIMENT

The HEMT structure was grown on a semi-insulating SiC substrate by metalorganic chemical vapor deposition. The layer structure employed 2 µm of undoped GaN grown at 1050 °C, 25 nm of undoped Al$_{0.2}$Ga$_{0.8}$N, and a 5 nm undoped GaN cap. A growth rate of 1.0 µm·h$^{-1}$ was used for all deposition. Ohmic contacts were formed by lift-off of electron-beam (e-beam) evaporated Ti/Al/Pt/Au, which was annealed at 850 °C for 30 s to minimize contact resistance. The Schottky gates of e-beam deposited Ni/Au were formed by conventional optical lithography with 1 µm gate length. The gate width was 100 µm. Mesa isolation of the devices was formed by inductively coupled plasma etching with Cl$_2$/Ar. Both HEMTs and transmission line patterns (TLM) were present on the mask set.

The HEMTs were irradiated with 2 MeV Ge$^+$ at doses from $5 \times 10^{10}$ to $5 \times 10^{12}$ cm$^{-2}$. The projected range of these ions is $\sim$0.65 µm in the HEMT structure from the stopping and range of ions in matter (SRIM) program, which places the end of range of the ions in the GaN buffer below the active layers. The SRIM simulation data are shown in Fig. 1. The dc characteristics of the HEMTs were measured before and after irradiation with a Tektronix curve tracer 370 A and an HP 4156 parameter analyzer. In addition to the changes in device parameters after irradiation, the HEMTs were also electrically stressed to determine any changes in reliability. The gate current, $I_G$, was plotted as a function of stressed drain...
voltage. The devices were stressed for 60 s at each drain voltage step, while grounding the source electrode and a constant voltage of $-6 \text{ V}$ were applied to the gate electrode. The stress started at 5 V of drain voltage and the voltage step was kept at 1 V. 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. Between each step stress, drain I–V, extrinsic transconductance, gate forward current biased from 0 to 1.5 V, and gate reverse current biased from 0 to $-10 \text{ V}$ were recorded. Self-heating effects were negligible based on the low drain-source currents under our test conditions.

III. RESULTS AND DISCUSSION

Figure 2 shows the drain current ($I_{DS}$)–drain voltage ($V_{DS}$) characteristics from the HEMT after irradiation with a dose of $10^{11} \text{ cm}^{-2}$ Ge ions. There was a decrease of $\sim 45\%$ in saturated $I_{DS}$ (Fig. 3) along with a concurrent decrease in transconductance ($g_m$). Both of these parameters were shown to have a strong dependence on dose. An increase in source-drain resistance ($R_{DS}$) with dose was additionally observed, also shown in Fig. 3. At the lowest fluence, $5 \times 10^{10} \text{ cm}^{-2}$, little change was observed for shifts in transconductance and $R_{DS}$. When the fluence increases to $1 \times 10^{11} \text{ cm}^{-2}$, the device characteristics begin to exhibit a linear trend with fluence. Overall, these changes are consistent with carrier removal and mobility reduction in the channel, reducing drain current and transconductance and increasing the drain resistance of the device. Note that the drain current does not linearly decrease with dose but tends toward saturation behavior. This would be expected as the number of deep traps created by displacement damage of the Ge ions approaches the carrier density in the channel of the HEMT. Additionally, the threshold voltage shifted to more positive values for increasing dose, as shown in Fig. 4. Two apparent regimes of degradation appear for $V_{TH}$ shift. Trap formations due to irradiation can result in a redistribution of charges which can ultimately affect the field profile and result in a shift of threshold voltage. Moreover, threshold voltage can also be affected by a decrease of carriers in the channel.

The gate leakage current decreased with dose, as shown in Fig. 5. At the lowest dose, $5 \times 10^{10} \text{ cm}^{-2}$, the increase in

![Fig. 1. (Color online) SRIM simulation of ion stopping profile for 2 MeV Ge ions in the AlGaN/GaN HEMT structure.](image1)

![Fig. 2. (Color online) Drain I–Vs of HEMTs before and after irradiation with 2 MeV Ge$^+$ ions at a dose of $10^{11} \text{ cm}^{-2}$.](image2)

![Fig. 3. (Color online) Percent changes in saturated drain current, transconductance, and source drain resistance as a function of Ge$^+$ dose.](image3)

![Fig. 4. Shift in threshold voltage of Ge$^+$ irradiated HEMTs as a function of ion dose.](image4)

barrier height compared to a fresh device is relatively small, only 0.05 eV. However, as the fluence is increased to the maximum of \(5 \times 10^{12} \text{ cm}^{-2}\), the shift in the barrier height is quite substantial, with an increase of 0.11 eV. To understand the mechanism further, we probed the on-chip TLM patterns receiving the same dose. Those irradiated with a dose of \(5 \times 10^{10} \text{ cm}^{-2}\) showed \(\sim 4 \times\) increase in sheet resistance and a 75% increase in specific contact resistance. TLM patterns irradiated at \(5 \times 10^{13} \text{ cm}^{-2}\) and \(5 \times 10^{12} \text{ cm}^{-2}\) exhibited nA current postirradiation (100 mA prior to irradiation). Significant damage due to heavy ions, in the form of simple defects such as \(V_{Ga}, V_N, Ga_i, N_i\), has been observed for group IV implantation into GaN. Furthermore, the incorporation of Ge in the lattice will also result in increased coulomb scattering.

All of these data are consistent with a decrease in electron concentration and mobility in HEMT channel. There was no systematic effect of gate width or length (gate length from 0.1 to 1 \(\mu\)m and width from 100 to 200 \(\mu\)m) on the degree of degradation in device parameters. Reverse recovery switching times in the HEMTs were unaffected by the Ge\(^+\) fluences we investigated. In contrast to proton implantation with moderate doses, which does not lead to high sheet resistivities of the implanted layers, the use of heavier ions like Ge\(^+\) causes the sheet resistivity to be greatly increased. The basic degradation mechanism is still carrier loss from the channel and mobility reduction as a result of trap formation in the AlGaN layer and in the GaN buffer.

We also found that Ge\(^+\) irradiation had a profound effect on the response of the HEMTs to subsequent electrical stressing. Figure 6 shows the gate current during typical off-state step-stresses of AlGaN/GaN HEMTs prior to and post Ge\(^+\) irradiation. The critical voltage, \(V_{\text{crit}}\), of the off-state step stress was defined as the onset of a sudden \(I_G\) increase during the stress. Typical \(V_{\text{crit}}\) for electrical degradation of virgin (unirradiated) HEMTs ranged from 13 to 15 V. By sharp contrast, no such critical voltage was detected for devices after Ge\(^+\) irradiation even up to a drain bias of +35 V, which is the limit of our apparatus. The same results were observed for devices after 5, 10, or 15 MeV proton irradiation with different doses ranging from \(2 \times 10^{11}\) to \(2 \times 10^{15} \text{ cm}^{-2}\). The off-state stress current at the beginning of the step-stress follows the same trend with dose as do the gate currents, with the reference gate current being lower than all the irradiated samples. The introduction of defects by ion irradiation clearly has a major effect on the electric field distribution near the gate, since the degradation in HEMTs during this type of electrical stressing is believed to come from field-driven mechanisms. It was previously reported that the degradation in dc characteristics after the off-state stress in GaN-based HEMTs was irreversible.

IV. SUMMARY AND CONCLUSIONS

In conclusion, we have demonstrated significant improvement of reliability of AlGaN/GaN HEMTs exposure to 2 MeV Ge\(^+\) irradiation. The critical voltage for off-state electrical step-stress was increased from \(\sim +13 \text{ V}\) to above +35 V. The gate current of the HEMTs was decreased by roughly half after a dose of \(10^{13} \text{ cm}^{-2}\) Ge\(^+\), showing these ions produce much more device degradation than protons. Degradation in materials properties and device performance is mainly due to carrier trapping and mobility reduction by radiation damage. In general, radiation effects in GaN with light ions can be reasonably well understood based on a picture in which the main radiation defects are due to shallow \(V_N\) and deep Ga\(_i\) donors and deep \(V_{Ga}\) and \(N_i\) acceptors. This model places \(V_N\) donors near \(E_c - 0.06 \text{ eV}\), Ga\(_i\) doubly charged donors near \(E_c - 0.8 \text{ eV}\), \(V_{Ga}\) acceptors near \(E_v + 1 \text{ eV}\), and \(N_i\) acceptors near \(E_c - 1 \text{ eV}\). However, with heavier ions, the trap levels created by radiation damage in GaN tend to be deeper in the bandgap and show more complex annealing behavior. To further understand the reasons for the changes in device performance, future work will involve Ge\(^+\) irradiation of the unprocessed AlGaN/GaN heterostructures, followed by characterization by Hall, deep level transient spectroscopy, and photoluminescence measurements. The results in this paper are a start toward a better understanding of heavier ion damage effects in GaN.
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