Effect of Surface Passivation and Substrate on Proton Irradiated AlGaN/GaN HEMT Transport Properties

J. C. Gallagher, T. J. Anderson, A. D. Koehler, N. A. Mahadik, A. Nath, B. D. Weaver, K. D. Hobart, and F. J. Kub

*American Society for Engineering Education Postdoc Fellow residing at the U.S. Naval Research Laboratory, Washington, DC 20375, USA
bU.S. Naval Research Laboratory, Washington, DC 20375, USA
cGeorge Mason University, Fairfax, Virginia 22030, USA

In this work, we fabricate Van der Pauw structures on AlGaN/GaN high electron mobility transistors (HEMTs) with both SiN and AlN passivation layers and both SiC and GaN substrates to study temperature dependent electron transport properties of 2 dimensional electron gases (2DEG) in as-fabricated and proton irradiated devices. We confirm that using a GaN substrate or AlN passivation layer enhances the mobility particularly at low temperatures, though this enhancement is greatly reduced upon irradiating the samples with high proton fluences. Our results suggest that the sheet density may be affected by Al diffusion in the sample creating electron donating impurities, which freeze out around 200 K and are more prominent in AlN passivated samples and minimized by using a GaN over a SiC substrate. Additionally, we show that a large dose of radiation forms traps in the AlGaN layer, which drop the sheet density at high proton fluences.

Manuscript received August 14, 2017. Published September 16, 2017. This paper is part of the JSS Focus Issue on GaN-Based Electronics for Power, RF, and Rad-Hard Applications.

GaN, among other wide bandgap semiconductors, is of considerable interest for next-generation energy efficient, high performance devices because their high electron mobility and high breakdown voltage allows them to operate at higher voltages, frequencies, and temperatures than current Si- or GaAs-based devices. One application is the production of AlGaN/GaN high electron mobility transistors (HEMTs) for microwave power amplifiers, making the study of these devices robustness in high energy proton radiation important for potential space applications.1–3

The robustness of GaN-based devices in radiation has been well documented.2,4–6 It has been shown that AlGaN/GaN HEMTs have minimal changes in resistance, mobility, and device performance with MeV scale proton fluences of 1E13 H+ /cm2 while larger fluences (1E14 H+ /cm2) can create charge traps, which reduce the electron mobility and increase the carrier concentration.7–9

Several studies have shown that AlGaN/GaN HEMTs are highly sensitive to their substrates and passivation layers. In particular, it has been shown that switching to a AlN-passivated layer improves transistor performance,10 while switching to a GaN substrate reduces threading dislocation densities by 4 orders of magnitude.2,3,11

Previous experimental and theoretical studies have determined temperature dependent AlGaN/GaN Hall effect measurements result in the mobility being limited by piezoelectric scattering and ionized impurity scattering at low temperatures and phonon scattering at high temperatures.12–14 However, the effect of radiation on these properties has not been examined. A Hall effect study on irradiated samples at low temperatures could help understand the types of defects caused by radiation and may suggest solution to minimizing them. This paper discusses the effect of radiation fluence, substrate composition, and temperature on the transport properties of AlGaN/GaN HEMTs.

Experimental

Sample preparation.—Three c-plane AlGaN/GaN HEMT devices were fabricated using process sequences previously described.11 GaN (2.2 μm) then 20 nm Al0.25Ga0.75N was deposited on SiC and GaN using metal organic chemical vapor deposition followed by a growth of 100 nm amorphous SiN as a surface passivation to create Samples A and B shown in Figure 1. To study the passivation effects, a third sample (Sample C in Figure 1) was fabricated under the same conditions as Sample A, except a 10 nm crystalline AlN passivation layer was deposited instead. The samples were cut, patterned and irradiated with 2 MeV protons at fluences of 1E13, 1E14, and 6E14 H+ /cm2. Using photolithography, the films were fabricated into Van der Pauw Hall using a C1 inductively coupled plasma etching followed deposition AlTiAu to serve as an ohmic contact. The quality of the samples is discussed in our previous work.5,11

High resolution X-ray diffraction.—High resolution X-ray diffraction (HR-XRD) was performed on as grown and irradiated Sample C using the Rigaku Smartlab diffractometer equipped with a 9 kW Cu rotating anode. A multilayer mirror and four bounce channel cut Ge (220) monochromator was used to obtain Cu Ka1 incident radiation with minimal vertical divergence. A computer controlled six-axis vertical goniometer was used to align the sample to obtain precise lattice parameters. Symmetric (0002) scans were performed to obtain out-of-plane lattice constants and asymmetric (20–24) reciprocal space mapping was performed to obtain the in-plane lattice constants (see Table I).

The symmetric HRXRD 2θ–θ scans are shown in Figure 2. Upon irradiation, the AlGaN peak shifts to the left thereby increasing the lattice constant. This indicates that the Al content in the film slightly reduces. The lattice parameters and computed Al content are listed in Table I. This suggests that the irradiation may cause Al to diffuse across the AlGaN/GaN barrier.

Hall measurements.—Hall measurements were performed using the Keithly 4200 semiconductor characterization system and the LakeShore CRX-VF Probe Station using currents ranging from 10–100 μA and fields ranging from 0.1–1 T. Van der Pauw’s calculations produced consistent resistivity’s (ρ), electron mobilities (μ), and sheet densities (n) to at least 3 significant digits at all measured currents and fields for all samples with results shown in Figure 3.

Dynamic I-V measurements.—To test the trap density in the materials, similar HEMT devices from our previous research11 were irradiated at fluences ranging from 1E12–6E14 H+ /cm2. Dynamic I-V

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analysis was taken with the Accent Optical Technologies DIVA system to determine the dynamic on resistance ($R_{on,\text{DYN}}$) at $V_{DS} = 25$ V (see Figure 4). At low fluences, the results remain fairly constant with respect to temperature; however, all samples eventually have $R_{on,\text{DYN}}$ increase at $4 \times 10^{14}$, $1 \times 10^{14}$, and $4 \times 10^{14}$ H$^+$/cm$^2$ for Samples A, B, and C respectively. This increase corresponds to a sudden drop in $n_s$ (see Figures 3h–3i).

Figure 2. XRD plot of the AlGaN peak for Sample C.

Discussion

The results of the Hall measurements on Sample A (Figures 3a, 3d, and 3g) has properties similar to previous research. When unirradiated, the mobility and resistivity are dominated by phonon scattering at high temperatures and a combination of piezoelectric, polar optical, and ionized impurity scattering at lower temperatures with a sharp transition around 220 K. The sheet density decreases with increasing temperature, which has been attributed to a decrease in both spontaneous and piezoelectric polarization at the interface.

A small dose of radiation ($1 \times 10^{13}$–$1 \times 10^{14}$ H$^+$/cm$^2$) causes a small drop in mobility, a slight increase in resistivity, a less sharp 220 K transition, and minimal change in sheet density. Higher doses ($6 \times 10^{14}$ H$^+$/cm$^2$) cause a large drop in sheet density due to formation of traps in the AlGaN layer that donate electrons as confirmed by an increase in $R_{on,\text{DYN}}$ (see Figure 4). These traps can be thermally excited at temperatures above 200 K as evident by the sheet density increasing with respect to temperature (see Figure 3g).

Changing to a GaN substrate (Sample B) yields a slight decrease in resistivity and increase in electron mobility (see Figures 3b and 3e) due to the absence of strain in the homoepitaxially grown GaN layer. Additionally, the 220 K phase transition is absent. These effects may be a result of the reduced threading dislocation density in homoepitaxially grown GaN. After irradiation, the mobility and resistivity drop to similar values to Sample A since impurity scattering is now the dominant factor. The sheet density (Figure 3h) drops at lower fluences due to increased electron donor traps in the AlGaN layer; however, these traps are deeper since they are still frozen out at room temperature.

Replacing the SiN passivation with AlN produces several major effects. The unirradiated samples have improved mobility over the SiN passivated sample and a smaller sheet density. After irradiation, the electron donating traps form at lower fluences possibly due to diffusion of Al atoms from the AlN layer. This correlates well with the epitaxial strain and width of the AlGaN XRD peak (see Table I). Since the AlN layer has a positive fixed charged layer at its AlGaN interface, the increased strain will decrease the charge of this layer causing the sheet density at the AlGaN/GaN interface to increase.

Conclusions

In conclusion, the effect of substrate and passivation layer on the transport properties of proton irradiated AlGaN/GaN HEMTs was
studied. Switching from SiC to GaN substrates or from SiN to AlN passivation yields an increased electron mobility at low fluence though all samples having similar values after high fluences of irradiation regardless of substrate or passivation. Dynamic IV measurements confirm that high levels of irradiation create electron trap layers in the AlGaN layer, which corresponds to a drop in sheet density and an increase in c-plane strain as confirmed with X-ray diffraction. The irradiation creates electron donor defects that freeze out around 200 K. These defects appear much stronger in the AlN passivated samples thus we speculate it is due to diffusion of Al atoms caused by the radiation; however, this diffusion appears to be less extreme or absent when the MOCVD GaN is grown homoepitaxially thus unstrained.

Acknowledgments

Work at the U.S. Naval Research Laboratory is supported by the Office of Naval Research.

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