Effect of Surface Passivation on Current Collapse of Proton-Irradiated AlGaN/GaN HEMTs

Andrew D. Koehler[1], Travis J. Anderson[1], Marko J. Tadjer[1], Bradley D. Weaver[1], Jordan D. Greenlee[2], David I. Shahin[3], Karl D. Hobart[1], Francis J. Kub[1]

[1]Naval Research Laboratory, Washington DC 20375
e-mail: andrew.koehler@nrl.navy.mil Phone: 202-404-6788
[2]NRC Postdoctoral Fellow Residing at NRL
[3]University of Maryland, College Park

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Abstract

Irradiating AlGaN/GaN high electron mobility transistors (HEMTs) with 2 MeV protons results in an increase in the dynamic ON-resistance (R_{ONDYN}). The amount of R_{ONDYN} degradation is more severe than what is observed in steady-state or Hall effect measurements. Radiation-induced defects located in close proximity to the two-dimensional electron gas (2DEG) trap electrons, which is responsible for the large increase in R_{ONDYN}. Therefore, surface passivation is critical. Conventionally, GaN HEMTs are passivated by plasma enhanced chemical vapor deposition (PECVD) SiN. However, after irradiation, SiN passivated HEMTs devices show severe R_{ONDYN} degradation, increasing from 21.4 Ohm-mm to 4,888 Ohm-mm (22,750%) at an OFF-state quiescent stress of 50 V. The impact of irradiation on the current collapse of GaN HEMTs with alternative passivation schemes are investigated including optimized PECVD SiN, in situ SiN, atomic layer epitaxy (ALE), and combinations of these.

INTRODUCTION

GaN-based high electron mobility transistors (HEMTs) are promising candidates for next-generation RF and high-voltage power switching applications, particularly for space applications, due to improved size, weight, power, and the ability to operate at elevated temperatures. Long-term non-ionizing damage caused from high-energy particles, such as protons from cosmic rays, solar particle events, and Van Allen radiation belts can generate defects, degrading performance and reliability. The DC characteristics of GaN HEMTs are relatively insensitive to proton irradiation [1-3]. However HEMTs with conventional plasma enhanced chemical vapor deposition (PECVD) SiN surface passivation show significantly degraded dynamic ON-resistance after proton irradiation [4]. Electrons trapped at radiation-induced defect states in the passivation layer deplete the two-dimensional electron gas (2DEG) sheet carrier density (n_s) [5]. This work investigates alternative passivation schemes for improved radiation tolerance of the current collapse and dynamic ON-resistance (R_{ONDYN}). Recently, improvements in the unirradiated dynamic ON-resistance of GaN HEMTs with atomic layer epitaxy (ALE) AlN passivation layers have been demonstrated [6]. High quality SiN layers grown *in situ* in the metal organic chemical vapor deposition (MOCVD) reactor also offer potential of improved current collapse [7, 8]. In this work, we investigate the radiation tolerance of GaN HEMTs with a variety of surface passivation schemes.

EXPERIMENT

AlGaN/GaN HEMTs structures with and without a 10 nm *in situ* grown SiN capping layer were fabricated by first performing mesa isolation with Cl_2 based inductively coupled plasma etching. Then, ohmic Ti/Al/Ni/Au (20/120/40/80 nm) contacts were deposited by electron beam evaporation followed by a rapid thermal anneal at 850 °C for 30 seconds. Then, Ni/Au (20/200 nm) Schottky gate metal was deposited by electron beam evaporation. The HEMTs were then passivated, and contact windows were open to expose the contact pads.

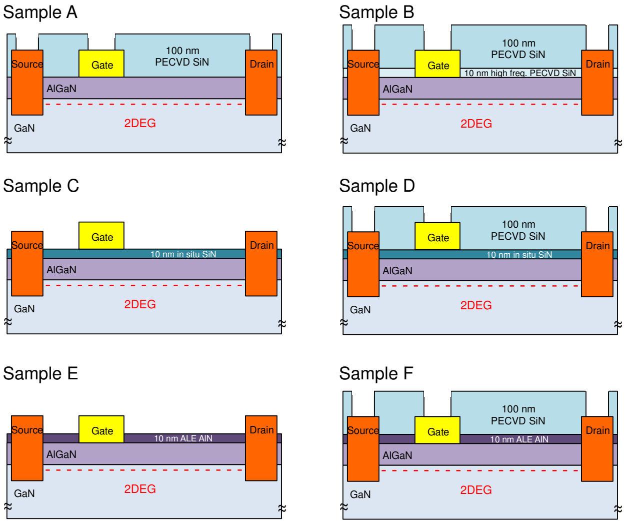

Figure 1. Schematic cross-sections of GaN HEMTs with various passivation schemes under investigation

TABLE I. Dynamic ON-Resistance with quasi-static and OFF-state quiescent stress

Sample	Passivation	Dynamic ON-Resistance (Ohm-mm)			
		$(V_{GSQ}, V_{DSQ}) = (0, 0)$		$(V_{GSQ}, V_{DSQ}) = (V_T – 2, 50)$	
		As Fabricated	After 6x10^{14} H^+/cm^2	As Fabricated	After 6x10^{14} H^+/cm^2
A	100 nm PECVD SiN	9.1	14.7	21.4	4,888
B	10 nm high frequency PECVD SiN + 100 nm PECVD SiN	6.6	10.7	27.3	600.1
C	10 nm *in situ* SiN	21.5	–	>>10,000	–
D	10 nm *in situ* SiN + 100 nm PECVD SiN	6.2	10.7	10.3	41.6
E	10 nm ALE AlN	6.5	9.2	13.3	20.7
F	10 nm ALE AlN + 100 nm PECVD SiN	6.4	9.6	12.1	30.1

The various passivation schemes under investigation are illustrated in Figure 1. Sample A has 100 nm of a conventional mixed high/low frequency PECVD SiN passivation, deposited after the gate metallization. The PECVD conditions are 300 °C, 20 W, 650 mT, 20 sccm SiH_4, 23.5 sccm NH_3, 980 sccm N_2, 13/7 sec. high/low frequency pulsed power, ~10 nm/min deposition rate. The ratio of the HF and LF cycles' duration in this process was optimized to minimize stress in the film. The high frequency was 13.56 MHz and low frequency was 100-360 kHz. Sample B is a PECVD SiN passivation layer where the first 10 nm of the PECVD SiN was high frequency plasma first, followed by the same 100 nm of mixed frequency PECVD SiN. Sample C is a HEMT structure with 10 nm of *in situ* SiN layer and no additional passivation. Sample D is a HEMT with 10 nm of *in situ* SiN with the additional 100 nm of mixed frequency PECVD SiN. Sample E has 10 nm of ALE AlN passivation, and Sample F has 10 nm of ALE AlN in addition to 100 nm of mixed frequency PECVD SiN passivation.

The HEMTs are exposed to 2 MeV protons, up to a fluence of 6 x 10^{14} H^+/cm^2. The protons stop 26 µm into the sample, deep in the substrate. As the protons transit through the devices, long-term damage is created. Pulsed *I-V* measurements with and OFF-state quiescent voltage stress is applied to quantify the effectiveness of the surface passivation before and after irradiation. The device is held at a gate quiescent point (V_{GSQ}) of V_T – 2 V and drain quiescent biases (V_{DSQ}) up to 50 V while the device is pulsed to obtain the transfer characteristics at V_{GS} = 0 V. The dynamic ON-resistance is then extracted.

Results and Discussion

Table I summarizes the dynamic ON-resistance values for each of the HEMTs before and after irradiation. Before irradiation, at the quasistatic quiescent bias condition, where V_{GSQ} = 0 V and V_{DSQ} = 0 V, each of samples demonstrate comparable R_{ONDYN} (6.2 to 9.1 Ohm-mm) except for Sample C (21.5 Ohm-mm). The *in situ* SiN layer alone implemented in Sample C is insufficient at providing passivation for the HEMT, even before radiation exposure. This is also seen in the current collapse of Sample C at V_{GSQ} = V_T – 2 V and V_{DSQ} = 50 V, which is large, therefore Sample C was omitted from irradiation experiments. Before irradiation, the ALE AlN passivated HEMTs show the best current collapse (Samples E and F) under OFF-state stressing, and the PECVD SiN passivated HEMTs (Sample A and B) show the largest current collapse before irradiation. The dynamic ON-resistance response after irradiation of 6 x 10^{14} H^+/cm^2 2 MeV protons for Samples A, B, D, E, and F are comparable at the quasistatic quiescent bias conditions ranging from 9.2 to 14.7 Ohm-mm. This degradation is comparable to the degradation observed in the steady state parameters [1]. However, the dynamic response during OFF-state drain voltage stress differs greatly depending on the surface passivation implemented.

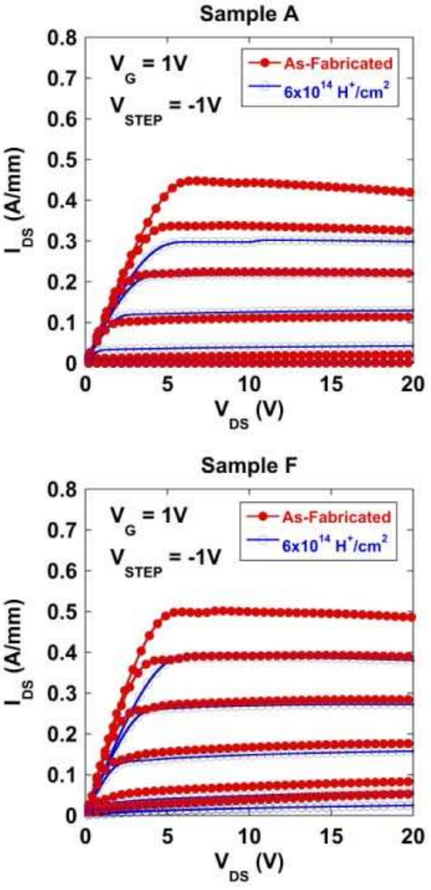

Figure 2. Steady-state I-V curves for Sample A and Sample F, which are representative of the overall changes observed for each sample.

The steady state I-V curves for Samples A and F, which are representative for how the steady-state characteristics behave after irradiation is shown in Figure 2. Figure 3 shows the dynamic ON-resistance of Sample A and Sample F before and after irradiation at the final fluence of of 6 x 10^{14} H^+/cm^2 2 MeV protons, under OFF-state quiescent drain voltage stress. It is observed that Sample A after irradiation is significantly collapsed. Sample F shows significant improvement, with drastically improved current collapse

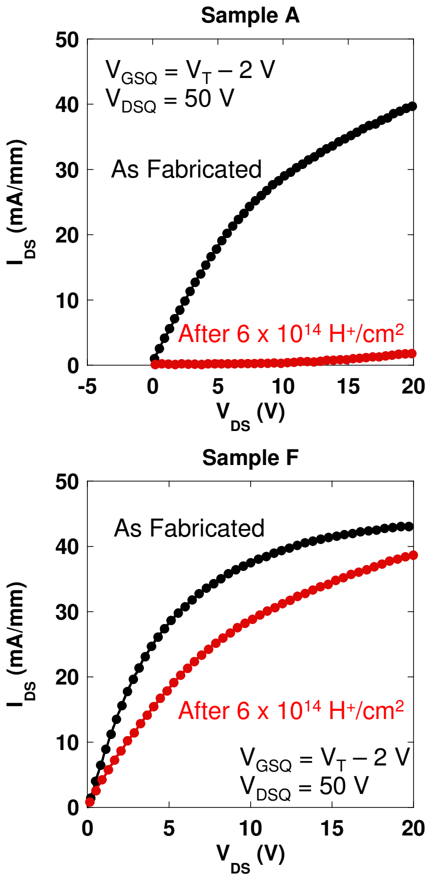

Figure 3. Dynamic ON-state drain current (at $V_{GS} = 0$ V) under OFF-state quiescent stressing with $V_{DSQ} = 50$ V for Samples A and F, before and after irradiation.

Figure 4 illustrates the dynamic ON-resistance as a function of the OFF-state drain quiescent stress of each sample before and after radiation. The PECVD-passivated HEMTs (Samples A and B) show extreme current collapse. Sample B demonstrates slightly improved current collapse compared to Sample A. Sample C, with10 nm of *in situ* SiN passivation only was ineffective at passivating the 'as fabricated' HEMT, and therefore was omitted from irradiation. Sample D shows significantly improved passivation after irradiation. The ALE AlN passivated HEMTs (Samples E and F) both are superior at passivating HEMTs and mitigating current collapse after proton irradiation.

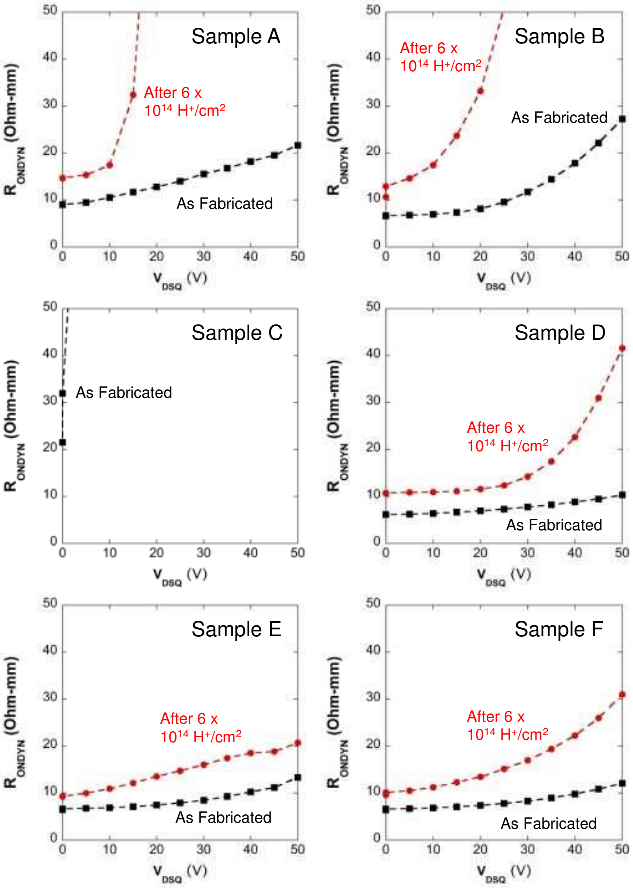

Figure 4. Dynamic ON-resistance of 2 MeV proton-irradiated HEMTs of each sample at various OFF-state quiescent voltage stresses before and after irradiation

CONCLUSIONS

Radiation-induced degradation in R_{ONDYN} is more severe than steady state and Hall effect parameters. Acceptor-type traps generated by the 2 MeV proton irradiation, which are located nearby the two dimensional electron gas (2DEG) trap electrons, increasing R_{ONDYN}. GaN HEMTs passivated by conventional plasma enhanced chemical vapor deposition (PECVD) SiN show severe R_{ONDYN} degradation, increasing from 21.4 Ohm-mm to 4,888 Ohm-mm (22,750%) at an OFF-state quiescent stress of 50 V. Improvements in the radiation response of current collapse was achieved by implementing 10 nm of *in situ* SiN in conjunction with 100 nm of PECVD SiN, 10 nm of ALE AlN, or 10 nm of ALE AlN in conjunction with 100 nm of PECVD SiN.

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ACRONYMS

ALE: Atomic layer epitaxy
HEMT: High Electron Mobility Transistor
ID: Drain current
N2DEG: Two-dimensional electron gas sheet carrier density
RONDYN: Dynamic ON-Resistance
VDSQ: Drain-to-source quiescent voltage
VGSQ: Gate-to-source quiescent voltage
VT: Threshold voltage
μ2DEG: Two-dimensional electron gas mobility
2DEG: Two-dimensional electron gas