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Effect of ^{60}Co gamma-irradiation on two-dimensional electron gas transport and device characteristics of AlGaN/GaN HEMTs

G. A. Umana-Membreno*[1], **J. M. Dell**[1], **G. Parish**[1], **B. D. Nener**[1], **L. Faraone**[1], **R. Ventury**[2], and **U. K. Mishra**[2]

[1] School of Electrical, Electronic and Computer Engineering, The University of Western Australia, Crawley WA 6009, Australia

[2] Dept. of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA

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The effect of ^{60}Co gamma-irradiation on $Al_{0.33}Ga_{0.67}N$/GaN high-electron-mobility transistors (HEMTs) has been investigated using DC and geometrical magnetoresistance measurements. The devices studied were of similar epitaxial structure, yet differed in the doping levels of the $Al_{0.33}Ga_{0.67}N$ barrier layer: (A) nominally undoped and (B) Si-doped with SiN_x passivation. Exposure to cumulative gamma-ray doses up to 20 Mrad(Si) is shown to induce significant changes in drain-current level, threshold voltage and gate leakage current level. Analysis of magnetoresistance characteristics measured at 80 K indicated that irradiation induced an increase in two-dimensional electron-gas (2DEG) density, which leads to negative threshold voltage shifts observable in the drain current versus gate voltage characteristics, attributable to the introduction of defect centers in the $Al_{0.33}Ga_{0.67}N$ layer and/or at the gate-AlGaN interface. The 2DEG mobility-concentration profiles are shown to remain approximately unchanged for doses up to 20 Mrad(Si). Device failure, evidenced as loss of gate control over the channel and/or excessive gate leakage, occurred after exposure to 30 Mrad(Si) for device A, whereas sample B failed after 20 Mrad(Si) total dose due to failure of half of the gate contact. Degradation of gate and source/drain contacts characteristics with total dose appears to limit the tolerance of the studied HEMTs to ^{60}Co gamma-irradiation.

1 Introduction

Due to their low susceptibility to radiation-induced displacement damage, GaN-based materials are attractive for device applications in high-energy irradiation environments [1, 2]. In particular, AlGaN/GaN high-electron-mobility transistors (HEMTs) are promising for satellite, military and nuclear applications due to their high speed, high output power and potential high tolerance to radiation-induced degradation.

While the low irradiation-induced defect production rates that characterize GaN are essential for radiation-hard AlGaN/GaN HEMTs, their reliability in high energy irradiation environments may be adversely impacted by the susceptibility of surfaces, interfaces, contacts and passivation layers to radiation-induced degradation. One of the earliest indications of such effects in GaN-based devices can be found in the report of Fang *et al*. [3], where leakage current degradation in GaN Schottky diodes was noted after exposure to 1 MeV electrons. More recently, we have reported that gamma-irradiation induced damage at the metal-semiconductor interface limits the radiation-hardness of Ni/GaN diodes [4]. For AlGaN/GaN HEMTs,

* Corresponding author e-mail: umana-ga@ee.uwa.edu.au

energetic gamma-ray exposure has been shown to affect their DC and RF characteristics, yet these effects appear to be significant only after exposure to very high doses [5, 6].

In this report, we present results of a study on the effect ^{60}Co gamma-irradiation on 2DEG transport and low-drain bias DC characteristics of AlGaN/GaN HEMTs. Total gamma-ray doses up to 20 Mrad(Si) were employed to study two different devices with similar epitaxial structure yet with different $Al_{0.33}Ga_{0.67}N$ layer doping level and ungated access region surface treatment. Both devices consistently manifested radiation-induced changes in drain current level, negative threshold voltage shifts and increased gate reverse leakage current level. The results herein reported indicate that the total dose radiation tolerance of AlGaN/GaN HEMTs is limited by degradation at gate and source/drain contacts.

2 Device and experimental details

The devices were fabricated on $Al_{0.33}Ga_{0.67}N$/GaN heterostructures grown on c-plane sapphire by metal-organic chemical vapor deposition at the University of California, Santa Barbara. The epitaxial structures of the two representative devices selected for this study are: (A) 150 Å nominally undoped $Al_{0.33}Ga_{0.67}N$ on 3.4 μm semi-insulating GaN; (B) 150 Å Si-doped $Al_{0.33}Ga_{0.67}N$ on 3.4 μm semi-insulating GaN, with SiN_x surface passivating layer. The devices had split source geometry, gate widths of 100 μm and gate-lengths and drain-source separations of (A) 0.7 and 2.4 μm, and (B) 0.5 and 2.1 μm. The source and drain contacts were formed using alloyed Ti/Al/Ni/Au metallization.

The drain, source and gate current characteristics were measured for gate bias V_{GS} from below threshold voltage V_T up to 1 V, at a drain bias V_{DS} of 0.1 V. To minimize the effect of gate leakage on the drain current, an effective drain current characteristics obtained by averaging the measured drain and source currents. Since the device characteristics are likely to be affected by any unintentional thermal treatment and GaN-based HEMTs manifest significant device self-heating at high drain bias [4, 7], throughout the course of the present study possible unintentional annealing effects from device self-heating were avoided by employing applied drain voltages below 0.25 V. The measurements were performed at 80 K under dark conditions at magnetic field densities from 0 to 12 T. Exposure to cumulative gamma-ray doses from 1.5 to 20 Mrad(Si) was realized in an AECL ^{60}Co-irradiator at an average dose rate of 2 krad(Si)/min. During irradiation, the samples were held in a nitrogen ambient at room temperature with all contacts electrically shorted. Following irradiation, the devices were maintained at room temperature for at least 3 hours to ensure that device characteristics had settled after possible short-term post-irradiation device instabilities.

The as-fabricated devices exhibited relatively high parasitic series resistances of (A) 79 ± 6 and 46 ± 2 Ω, and (B) 47 ± 4 and 44 ± 2 Ω, at 80 and 300 K, respectively. Since high series resistance is known to adversely affect the accuracy of parameters extracted from magnetoresistance measurements, an analysis method was developed to extract 2DEG channel characteristics from total magnetoresistance. The analysis procedure assumes that the gate control of 2DEG channel can be adequately described by the conventional linear charge control model and that 2DEG transport is dominated by a single carrier; the ungated channel sheet resistance is assumed to be approximately equivalent to that of the gated channel at $V_{GS} = 0$ V. A detailed description of the method has been published elsewhere [8].

3 Results and discussion

Prior to device irradiation, device A exhibited higher series resistance at 80 K than at 300 K. This change in series resistance was accompanied by a negative shift in threshold voltage of ΔV_T of 0.34 ± 0.02 V from room temperature to 80 K. Assuming that the change in V_T arises from the thermal activation of defect centers in the $Al_{0.33}Ga_{0.67}N$ layer, the defect is calculated to be approximately 1.7×10^{18} cm^{-3}. Device B manifested superior characteristics with a much smaller negative ΔV_T of 0.09 ± 0.03 V over the same temperature range.

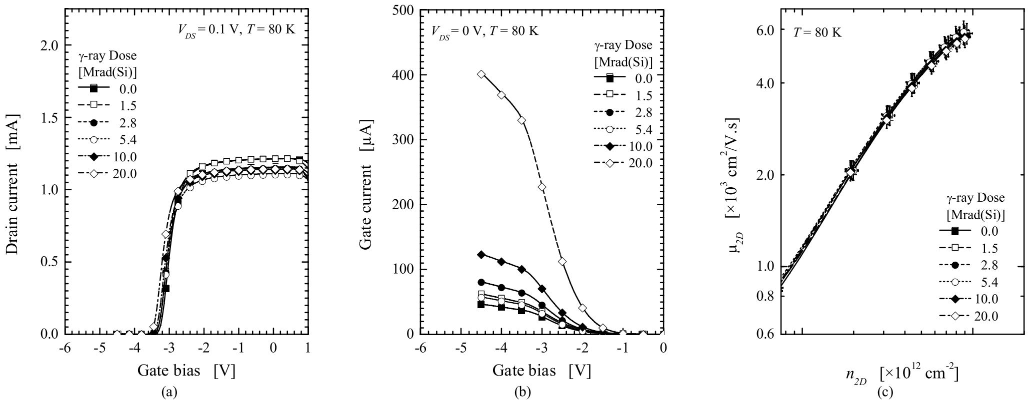

Fig. 1 Effect of ^{60}Co gamma-irradiation on the characteristics of device A (AlGaN/GaN HEMT $x = 0.33$ and undoped AlGaN layer): (a) Drain current, (b) gate leakage current, and (c) mobility-concentration profiles

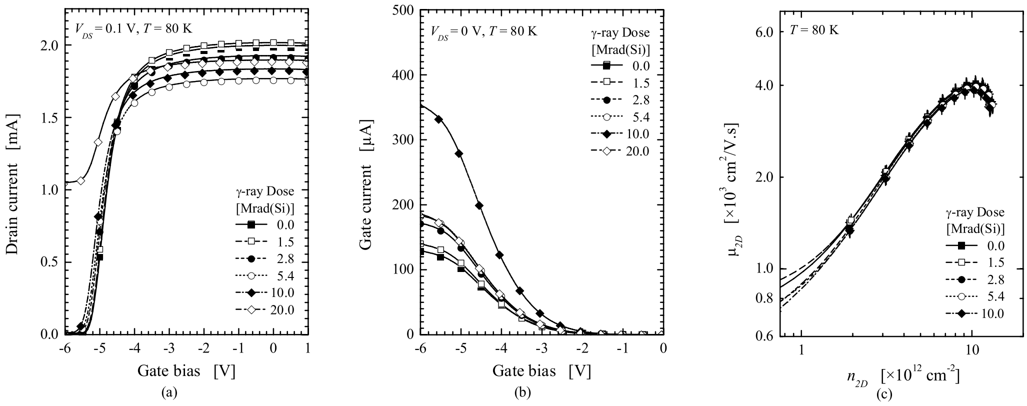

Fig. 2 Effect of ^{60}Co gamma-irradiation on the characteristics of device B (an AlGaN/GaN HEMT with $x = 0.33$, Si-doped AlGaN layer and SiN$_x$ passivation): (a) Drain current, (b) gate leakage current, and (c) mobility-concentration profiles

For both device samples, as shown in Figs. 1(a) and 2(a), irradiation induced a decrease in drain current level I_{DS} near V_{GS} = 0 V which reached a minimum after exposure to $\sim$5 Mrad(Si), and increased upon further irradiation. Both devices also exhibited a shift in threshold voltage toward more negative V_{GS} with increasing total gamma-ray dose. After exposure to an accumulated dose of 20 Mrad(Si), device B manifested significant channel conduction below threshold voltage and reduced gate leakage current, as evidenced in Figs. 2(a) and (b). This effect, attributable to failure of half of the split-geometry gate contact, is likely to be an anomaly unique to this device. Nevertheless, and as expected from the similarity in their epitaxial structure, both devices experienced similar gate leakage current degradation trends with dose. Even though the leakage current levels of device B were greater than those of device A, the magnitude and rate of the degradation with dose were almost identical; after 10 Mrad(Si), the ratio of gate current at V_T with respect to pre-irradiation value, I_g/I_{g0}, was 2.76 for device A and 2.79 for device B. A change in gate leakage current degradation trend with dose was noted at $\geq$ 5 Mrad(Si) in both devices. This indicates that, for the irradiation levels employed in this work, the surface passivation and intentional impurities in device B did not have a significant impact on device radiation susceptibility. Exposure to a total dose of

5 Mrad(Si) appears to mark the onset of a more severe radiation-induced degradation trend, consistent with previously observed effects in gamma-irradiated n-GaN Schottky diodes [4].

The extracted 2DEG transport parameters for devices A and B are shown in Figs. 1(c) and 2(c), respectively. The 2DEG sheet density increased with total gamma-ray dose resulting in negative ΔV_T of 0.198 ± 0.027 V for device A and 0.239 ± 0.030 V for device B, both after 10 Mrad(Si). The radiation-induced increase in 2DEG density is attributable to the introduction of defect centers in the $Al_{0.33}Ga_{0.67}N$ layer, with estimated concentrations of 9.7×10^{17} and 1.2×10^{18} cm^{-3} for devices A and B, respectively, as calculated from the negative shifts in V_T with accumulated dose. It should be noted that the increase in 2DEG charge, and shifts in V_T, can also be interpreted as arising from an increase in surface-state density at the metal-$Al_{0.33}Ga_{0.67}N$ interface. Interestingly, the 2DEG mobility-concentration profiles for device A remained approximately unchanged for doses up to 20 Mrad(Si), indicating negligible degradation in 2DEG mobility. A marginal degradation in 2DEG mobility was noted in device B. However, this degradation is significant only for n_{2D} $<1.8\times10^{12}$ cm^{-2}, or $V_{GS} < -4.5$ V; at higher n_{2D} densities the change in μ_{2D} falls within the error bounds of the extracted parameters. Exposure to 30 Mrad(Si) induced device failure in devices A due to loss of gate control over the channel and excessive gate leakage.

4 Conclusions

The magnetoresistance and DC characteristics of $Al_{0.33}Ga_{0.67}N$/GaN HEMTs exposed to energetic gamma-rays have been studied. The increased 2DEG density and threshold voltage shifts with dose are attributed to the introduction of defects centers in the $Al_{0.33}Ga_{0.67}N$ layer and/or at the gate-$Al_{0.33}Ga_{0.67}N$ interface. Significant degradation was observed after exposure to cumulative gamma-ray doses up to 20 Mrad(Si), which was manifest as changes in drain and gate leakage current levels with dose. Gate leakage current degradation appears to be the dominant degradation mechanism, as device failure due irradiation exposure was manifest in loss of gate control over the channel and excessive gate leakage. The results herein reported indicate device failure at significantly lower doses than those employed in published studies [5, 6]; this apparent discrepancy is likely to originate from thermal annealing effects associated with device self-heating at high drain biases. If this is the case, AlGaN/GaN HEMTs operated at high output power levels will manifest enhanced radiation hardness due to the annealing effects of device Joule heating.

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