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Influence of ^{60}Co γ-rays on dc performance of AlGaN/GaN high electron mobility transistors

B. Luo, J. W. Johnson, and F. Ren
Department of Chemical Engineering, University of Florida, Gainesville, Florida 32611

K. K. Allums, C. R. Abernathy, and S. J. Pearton[a)]
Department of Materials Science and Engineering, University of Florida, Gainesville, Florida 32611

A. M. Dabiran, A. M. Wowchack, C. J. Polley, and P. P. Chow
SVT Associates, Eden Prairie, New Mexico 55344

D. Schoenfeld
Department of Nuclear and Radiological Engineering, University of Florida, Gainesville, Florida 32611

A. G. Baca
Sandia National Laboratories, Albuquerque, New Mexico 87185

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AlGaN/GaN high electron mobility transistors (HEMTs) with different gate length and widths were irradiated with ^{60}Co γ-rays to doses up to 600 Mrad. Little measurable change in dc performance of the devices was observed for doses lower than 300 Mrad. At the maximum dose employed, the forward gate current was significantly decreased, with an accompanying increase in reverse breakdown voltage. This is consistent with a decrease in effective carrier density in the channel as a result of the introduction of deep electron trapping states. The threshold voltage shifted to more negative voltages as a result of the irradiation, while the magnitude of the drain–source current was relatively unaffected. This is consistent with a strong increase of trap density in the material. The magnitude of the decrease in transconductance of the AlGaN/GaN HEMTs is roughly comparable to the decrease in dc current gain observed in InGaP/GaAs heterojunction bipolar transistors irradiated under similar conditions. [DOI: 10.1063/1.1445809]

Despite remarkable progress in recent years in the performance of AlGaN/GaN high electron mobility transistors (HEMTs), there are still fundamental issues that need work.[1–12] One example is the observation that the rf powers obtained from GaN-based HEMTs is considerably lower than expected from the dc characteristics.[9,10] A second area of interest is the response of these devices to ionizing radiation, since it is expected that their high-power, high-temperature capabilities will be used in space-borne applications such as satellite communication systems in addition to the nuclear industry and military uses. It is expected that GaN-based electronic devices will be considerably more radiation hard than their more conventional GaAs-based counterparts due to the higher displacement energy of the nitride materials.[13] Several past reports have shown that AlGaN/GaN HEMTs are much more robust than their AlGaAs/GaAs counterparts to displacement damage caused by high energy (1.8–40 MeV) proton irradiation at doses corresponding to more than 100 years in low-Earth orbit.[14,15] In those experiments, relatively small changes (<30%) in extrinsic transconductance, drain–source current, and reverse breakdown voltage were observed.[15] In addition, the reverse recovery characteristics remained unchanged within experimental error, perhaps due to the small minority carrier lifetime in GaN.[16]

In this work, we report on the effects of high doses (up to 600 Mrad) of ^{60}Co γ-rays on the dc characteristics of AlGaN/GaN HEMTs. At the highest dose, reverse breakdown voltage (V_B) increased by up to a factor of two, threshold voltage (V_T) became more negative and extrinsic transconductance (g_m) decreased by 20%–30% depending on gate width and gate length. The results are consistent with the γ-irradiation causing a decrease in the effective channel doping through introduction of deep electron traps.

The HEMT structures were grown by molecular-beam epitaxy on (0001) sapphire substrates.[17] A low-temperature, 300 Å thick AlN buffer layer was followed by 2 μm of undoped GaN grown under Ga-rich conditions, 250 Å of undoped $Al_{0.2}Ga_{0.8}N$ and a 30 Å undoped GaN cap layer. The processing involved lift off of electron beam evaporated Ti/Al/Pt/Au for ohmic contacts or Ni/Au for Schottky gates. The ohmic metallization was annealed under N_2 at 850 °C for 30 s. The gate lengths were varied from 0.8–1.2 μm, with gate widths of 100, 150 or 200 μm. The dc characteristics were measured at 25 °C using a HP 4145B parameter analyzer. The devices were exposed to a 600Ci ^{60}Co source for accumulated doses of 300–600 Mrad. The calibration of dose was performed with radiometric films and ion chamber radiation meters.

Figure 1 shows forward (top) and reverse (bottom) current–voltage ($I-V$) characteristics from 1.2 μm gate length devices before and after 600 Mrad γ-dose. The gate leakage is significantly decreased in the low bias region (<0.5 V) where surface generation recombination is dominant and also at higher voltage, due to an increase in channel resistance. Since the resistivity of this GaN layer is propor-

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[a)] Electronic mail: spear@mse.ufl.du

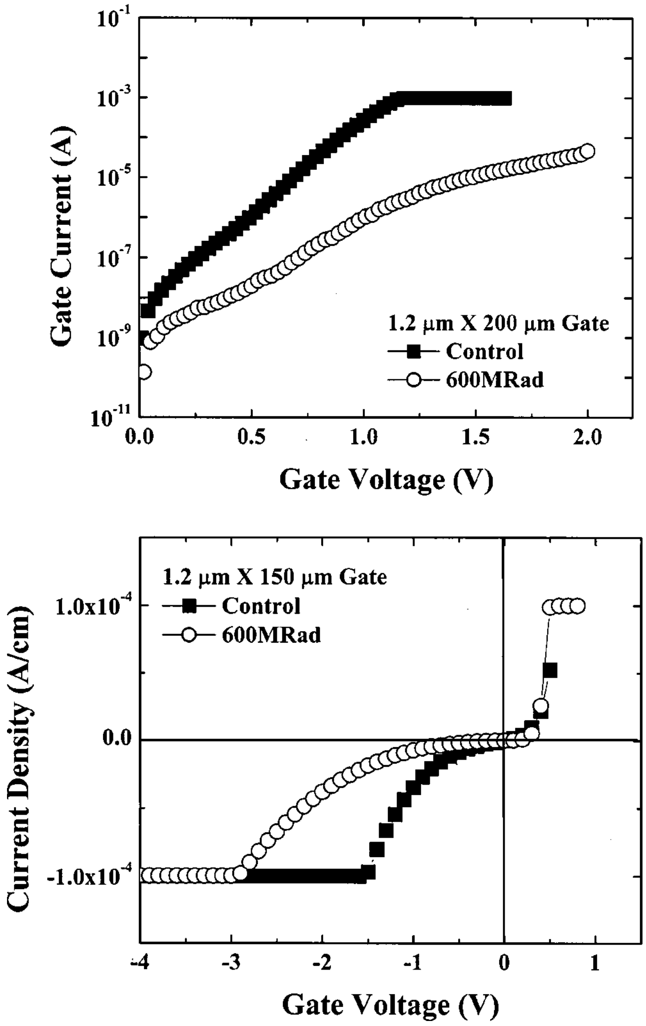

FIG. 1. Forward gate characteristics from 1.2×200 μm^2 HEMTs before and after γ-irradiation to 600 Mrad (top) and reverse breakdown characteristics from 1.2×150 μm^2 devices after irradiation at the same condition (bottom).

tional to the product $(n\mu)^{-1}$ (where n is the carrier density and μ the electron mobility), this increase can originate from decreases in either or both of these parameters. It is clear from the fact that V_B becomes more negative that the data is consistent with a reduction in effective doping in the channel by trapping into deep states created by the γ-irradiation.

Figure 2 shows the transfer characteristics of a HEMT before and after the 600 Mrad γ-dose. The threshold voltage increases in magnitude in irradiated devices. Since $V_{\mathrm{TH}} = V_{\mathrm{BI}} - e(N_d+N_T)a^2/2\epsilon$, where V_{BI} is the built-in voltage, N_D is the donor density in the AlGaN, N_T the trap density, a the active layer thickness, and ϵ the dielectric constant, then the γ-irradiation produces a net increase in N_d+N_T. This term is dominated by the increase in trap density. Note that the 300 Mrad γ-dose did not produce a significant change in any of the device parameters. For the 600 Mrad dose, the extrinsic transconductance g_m decreased by 20%–45%, depending on both gate length and width. Since $g_m = \partial I_D/\partial V_G$, the decrease originates in the reduced drain current due to the reduction of carrier density in the channel. Note that the reduction in g_m in the HEMTs is of a comparable magnitude to the reduction in dc current gain of high speed InGaP/GaAs heterojunction bipolar transistors (HBTs) irradiated under the same conditions. The doping levels in the HBTs are much higher than in the HEMTs (e.g., Base doping of 7×10^{19} cm^{-3}, emitter doping of 8×10^{18} cm^{-3}) and one would expect them to show much less effect of the irradiation. We feel this is a useful rule-of-thumb comparison to show the outstanding radiation hardness of the nitride materials system relative to the more conventional GaAs/AlGaAs.

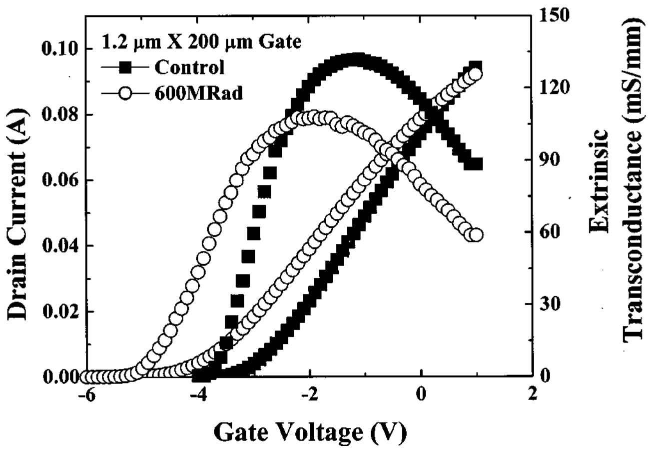

FIG. 2. Transfer characteristics for 1.2×200 μm^2 HEMTs before and after γ-irradiation to 600 Mrad dose.

Figure 3 shows drain–source current (I_{DS}) as a function of drain–source voltage (V_{DS}) characteristics before and after 600 Mrad exposure. The saturation I_{DS} increases slightly upon irradiation. This is most likely due to the higher resistance of the irradiated semiconductor material. This reduces the gate bias seen by the channel because part of this voltage is screened by the high resistance AlGaN layer under the gate contact and the recess region between the gate and the drain contact. There is also a decrease in the initial slope of the current at low bias, indicating a change in carrier mobility or density as discussed earlier.

There was also a pronounced effect of gate width on the changes in HEMT dc performance. Figure 4 shows the change in g_m as a function of gate width for the 600 Mrad γ-dose. The smaller devices suffer a larger change in g_m because of the decrease in effective channel doping and the more effective shielding of the gate bias in HEMTs with shorter gate width. Similarly large gate length (1.2 μm) de-

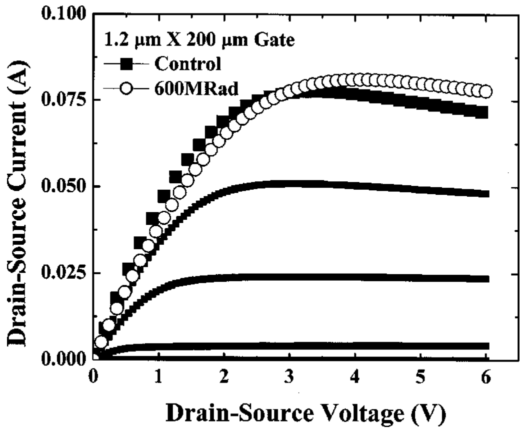

FIG. 3. $I_{\mathrm{DS}}-V_{\mathrm{DS}}$ characteristics from 1.2×200 μm^2 HEMTs before and after γ-irradiation to 600 Mrad dose. For the sake of clarity, only the uppermost curve is shown for the irradiated device.

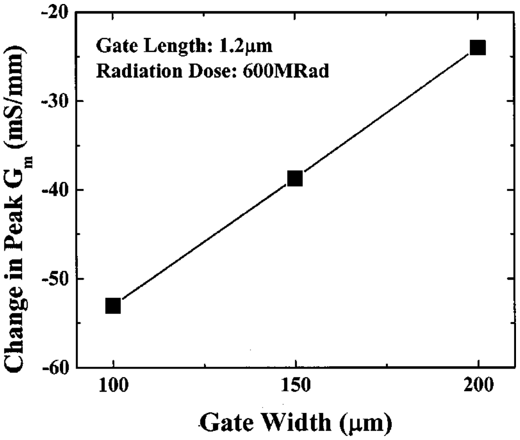

FIG. 4. Change in g_m as a function of gate width for 1.2 μm gate length devices irradiated with γ-rays to a dose of 600 Mrad.

vices showed smaller changes in g_m upon irradiation than shorter gate length (0.8 μm) HEMTs.

The effect of γ-irradiation in reverse breakdown voltage was also more pronounced in smaller gate width devices, as shown in Fig. 5. The bulk trap density depends on the total energy deposition per unit volume by the γ-rays, whereas surface traps would have a larger influence in devices with smaller area. Some preliminary measurements of reverse recovery characteristics showed no significant change as a result of the γ-irradiation. The switching times were $\sim 10^{-8}$ s for switching from -3 to $+2$ V. This is similar to the result for proton irradiation of AlGaN/GaN HEMTs.[15]

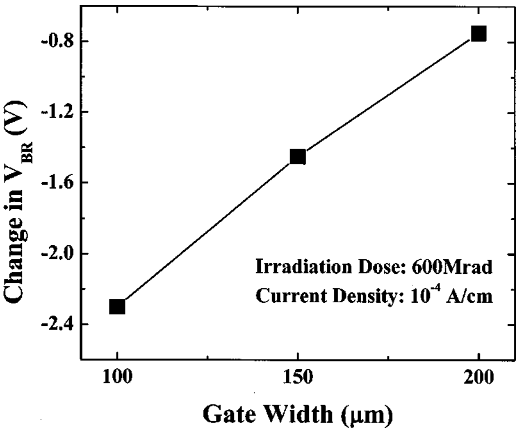

FIG. 5. Change in V_{BR} as a function of gate width for 1.2 μm gate length devices irradiated with γ-rays to a dose of 600 Mrad.

In conclusion, high dose (up to 600 Mrad) γ-irradiation of nitride-based HEMTs produced changes $\leqslant$45% in g_m for a range of gate lengths and widths. The change in device performance primarily resulted from a decrease in effective carrier density in the channel upon irradiation.

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