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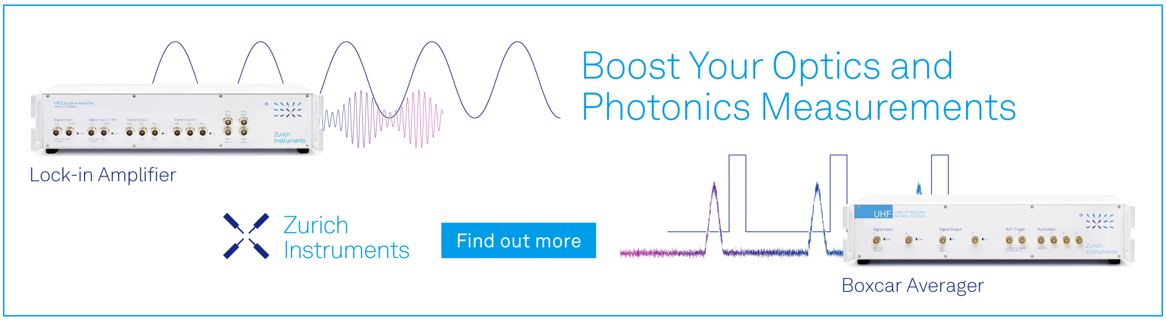

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Reducing proton radiation vulnerability in AlGaN/GaN high electron mobility transistors with residual strain relief

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ABSTRACT

Strain plays an important role in the performance and reliability of AlGaN/GaN high electron mobility transistors (HEMTs). However, the impact of strain on the performance of proton irradiated GaN HEMTs is yet unknown. In this study, we investigated the effects of strain relaxation on the properties of proton irradiated AlGaN/GaN HEMTs. Controlled strain relief is achieved locally using the substrate micro-trench technique. The strain relieved devices experienced a relatively smaller increase of strain after 5 MeV proton irradiation at a fluence of 5×10^{14} cm^{-2} compared to the non-strain relieved devices, i.e., the pristine devices. After proton irradiation, both pristine and strain relieved devices demonstrate a reduction of drain saturation current ($I_{ds,sat}$), maximum transconductance (G_m), carrier density (n_s), and mobility (μ_n). Depending on the bias conditions the pristine devices exhibit up to 32% reduction of $I_{ds,sat}$, 38% reduction of G_m, 15% reduction of n_s, and 48% reduction of μ_n values. In contrast, the strain relieved devices show only up to 13% reduction of $I_{ds,sat}$, 11% reduction of G_m, 9% reduction of n_s, and 30% reduction of μ_n values. In addition, the locally strain relieved devices show smaller positive shift of threshold voltage compared to the pristine devices after proton irradiation. The less detrimental impact of proton irradiation on the transport properties of strain relieved devices could be attributed to reduced point defect density producing lower trap center densities, and evolution of lower operation related stresses due to lower initial residual strain.

INTRODUCTION

Gallium nitride (GaN) is one of the most attractive wide-bandgap semiconductor materials for next generation electronics requiring high power, high frequency, high speed, and high temperature due to its excellent electrical, thermal, and optical properties.[1,2] The superior performance of GaN-based devices is the result of the large bandgap, high critical electric field, high electron saturation velocity and mobility, and good thermal conductivity.[3,4] One of the most promising GaN-based devices is the AlGaN/GaN high electron mobility transistor (HEMT), where the spontaneous and piezoelectric polarizations of GaN are utilized to form a two-dimensional electron gas (2DEG) at the AlGaN/GaN heterointerface providing high electron mobility and very low specific ON-resistance without any intentional doping.[5,6] Besides excellent electrical transport properties, the GaN-based devices demonstrate very good radiation tolerance due to the high displacement threshold energy of GaN resulting from its small lattice constants.[7–9] The GaN devices also show good ionization resistance and self-healing phenomena at room temperature.[10,11] The AlGaN/GaN HEMTs provide additional radiation hardness due to the very small cross section of the 2DEG channel, which modulates the transport properties of the device. As a result, GaN-based devices are very attractive for harsh radiation environment applications such as space exploration, satellite-based wireless communications, radar, defense electronics, and nuclear power plants.[12]

Electronic devices are susceptible to radiation induced degradation in harsh environments due to repeated exposure of high energy photons such as gamma and x rays, neutrons, and charged particles such as protons and alpha particles.[8,11] The energetic particles and photons degrade the device's performance through ionization and displacement damage. GaN-based devices also experience radiation induced degradation to some extent.[4,7,8,11] Extensive research has been reported in the literature on the proton irradiation effects on the transport properties of AlGaN/GaN HEMTs.[13–27] Studies have been performed on wide range of proton energy ranging from 100 keV to 105 MeV[18,26] and fluence values ranging from 1×10^{10} to 2×10^{16} protons/cm^2.[18,19] Noticeable degradation of GaN HEMTs is usually observed with proton energy greater than 2 MeV with fluence of $>1 \times 10^{14}$ protons/cm^2.[8] In general, at a fixed proton energy, the higher fluence level induces higher degradation of GaN HEMTs, whereas, at the fixed fluence level, lower proton energy shows more detrimental effect of GaN HEMTs. Lower energies produce larger non-ionizing energy loss (NIEL) within the 2DEG, resulting in a higher probability of defect generation. As a result, a higher number of defects are generated in the AlGaN barrier layer and the GaN buffer layer and/or the AlGaN/GaN interface, where the 2DEG layer is located. However, all of the proton irradiation studies of GaN HEMTs are primarily focused on the degradation of device performance relating to the type of defects and defect generation mechanisms as a function of different combinations of proton energy and fluence,[13,18,20,26–28] device heterostructures, substrates, and fabrication scheme.[14,29–34]

The unique heterostructure of AlGaN/GaN HEMTs inevitably introduces strain within the device layers, which originates from the mismatch of lattice constants and thermal expansion coefficients of active device layers and the substrate materials.[35,36] The study of strain effects on the performance of AlGaN/GaN HEMTs has achieved a lot of attention due to the strain dependency of 2DEG transport properties.[37–40] The combined effect of strain in the interfacial layers of 2DEG, i.e., the GaN, which could be under tensile or compressive strain depending on the substrate, and the AlGaN, which is mostly under tensile strain,[11,41] determines the overall strain status of the 2DEG. It has been reported that tensile strain increases the 2DEG conductivity by increasing the carrier density and mobility.[37,42,43] However, the existing strain literature of GaN HEMTs is mostly concerned with uniform strain achieved by mechanical bending,[39,40] cantilever structures,[37] different substrate materials,[36] and partial removal of the substrate.[43,44] But non-uniform strain or localized strain distribution is very prevalent in electronic devices arising from different device features such as contact pads, passivation layers, field plates, non-uniformity of the substrate itself, and process related non-uniformity. The impact of localized strain distribution along and across the device channel is mostly neglected due to the very small global average of localized strain, which apparently has an inconsequential response to the global transport properties of the device. The difficulty of controlling strain locally and the difficulty in accurate measurement of strain within a very small, confined region is also an impediment to study localized strain effects. Therefore, only a handful of research is available on the localized strain distribution effect on the performance and reliability of GaN HEMTs.[45–47]

The motivation for this research arises from the strain dependent performance of AlGaN/GaN HEMTs. The strain effects and proton irradiation effects on the performance of GaN HEMTs have been separately reported in the literature. However, no experimental study has been performed yet on the impact of strain on the proton irradiated GaN HEMTs, let alone localized strain. Using atomic scale simulations in combination with the Monte Carlo method and the carrier transport theory, Li *et al.*[48] recently have reported that compressive strain can enhance the proton irradiation tolerance of GaN HEMTs by reducing defect density, whereas the tensile strain can degrade the proton irradiation hardness. Therefore, it is important to experimentally investigate the synergistic effect of strain and proton irradiation in GaN HEMTs. In this research, we investigated the proton irradiation effect on the transport properties of localized strain relieved AlGaN/GaN HEMTs.

EXPERIMENTAL DETAILS

Commercially available depletion mode AlGaN/GaN HEMT dies (CGHV60008D, Wolfspeed®) on SiC substrates were used in this research. For localized strain relaxation, we employed the substrate micro-trenching technique by focused ion beam (FIB), a widely used method for controlled residual stress relief and measurement.[49,50] A 70 μm deep trench of $20 \times 30\,\mu\text{m}^2$ size was milled on the 100 μm substrate under each device channel of the six-fingered device using FEI Scios two dual beam FIB equipped with gallium ion (Ga$^+$) source. The details of strain relaxation by the substrate micro-trenching can be found in Ref. 51. The cross-sectional schematics of a single channel of the pristine and micro-trenched devices are shown in Fig. 1.

Proton irradiations were performed at the Korean Institute of Radiological and Medical Sciences using an MC 50 (Scanditronix) cyclotron. The proton energy was held constant at 5 MeV. The irradiated fluence was $5 \times 10^{14}\,\text{cm}^{-2}$ at a constant beam current of 10 nA. The irradiation time was 5089 s.

Micro-Raman spectroscopy was used to measure the strain in the GaN layer of the devices using a Horiba LabRAM HR Evolution coupled with 100×, NA = 0.9 microscope objective. The high-resolution Raman spectra were obtained using a 532 nm (Oxxious LCX-Nd:YAG) green laser with an incident power <4 mW, a confocal hole/slit set to 50 μm, an 1800 g/mm grating, and a Si array back illuminated deep depleted detector (Horiba-Synapse). The Raman maps were recorded with 2 and 0.5 μm step intervals along and across the device channel, respectively. The position and full width at half maximum (FWHM) of the peaks were extracted after fitting the Raman spectra using the Pseudo-Voigt peak fitting model. All electrical characterization was performed at room temperature on a Cascade 1200 probe station equipped with a Keithley 4200A-SCS semiconductor parameter analyzer.

RESULTS AND DISCUSSIONS

Stopping and Range of Ions in Matter (SRIM)[52,53] simulation was performed to obtain the energy loss of 5 MeV proton in the AlGaN/GaN heterostructure and irradiation induced vacancy distribution. The simulated total energy loss, i.e., the electronic energy

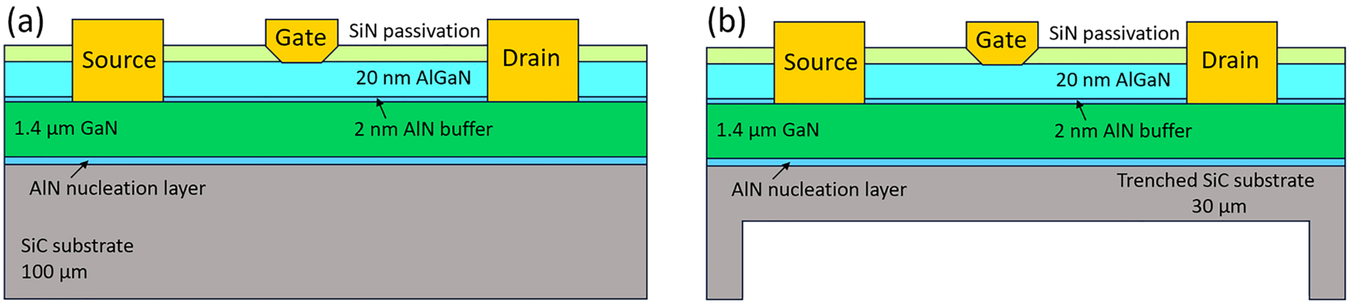

FIG. 1. Cross-sectional schematics of (a) pristine and (b) micro-trenched ($20 \times 30\,\mu m^2$) (along the plane of trenching, not drawn up to scale) devices.

loss and nuclear energy loss, as a function of projected penetration depth is shown in Fig. 2(a). The projected range of 5 MeV protons is higher than 200 μm, which suggests most of the ions pass through the ~102 μm AlGaN/GaN HEMT structure including the SiC substrate. The active device layers, i.e., the AlGaN and GaN layers, are located at a shallow penetration depth, below 0.3 μm thick SiN passivation layer. As a result, the energy loss in the active device layers is primarily by electronic stopping causing ionization. Most of the nuclear energy loss is deposited into the SiC below the HEMT structure. However, the high energy proton ions interact with the Schottky and Ohmic contacts of the device containing heavy elements such as gold and platinum. As a result, the bombarded proton ions scatter with lower energy into the 2DEG interface region creating vacancies and a cascade of defects by non-ionizing energy loss (NIEL). The distribution of gallium and nitrogen vacancies in the AlGaN and GaN layers as a function of penetration depth of 5 MeV proton ions is shown in Fig. 2(b). The density of gallium vacancies is found to be relatively higher compared to nitrogen vacancies due to the higher displacement energy of nitrogen.[13] Gallium vacancies act as acceptor like defects and nitrogen vacancies act as donor like defects. These defects are responsible for the degradation of 2DEG carrier density and mobility.[9,28,54–56]

The in-plane strain (ε_{xx}) in the GaN HEMTs was obtained by high-resolution micro-Raman spectroscopy. The ε_{xx} value was estimated using the frequency shift of the GaN E_2 (high) phonon mode compared to the strain free E_2 (high) phonon frequency.[36,57,58] The in-plane strain distribution before proton irradiation of the pristine and micro-trenched devices is shown in Fig. 3(a). The in-plane tensile strain values of the pristine devices

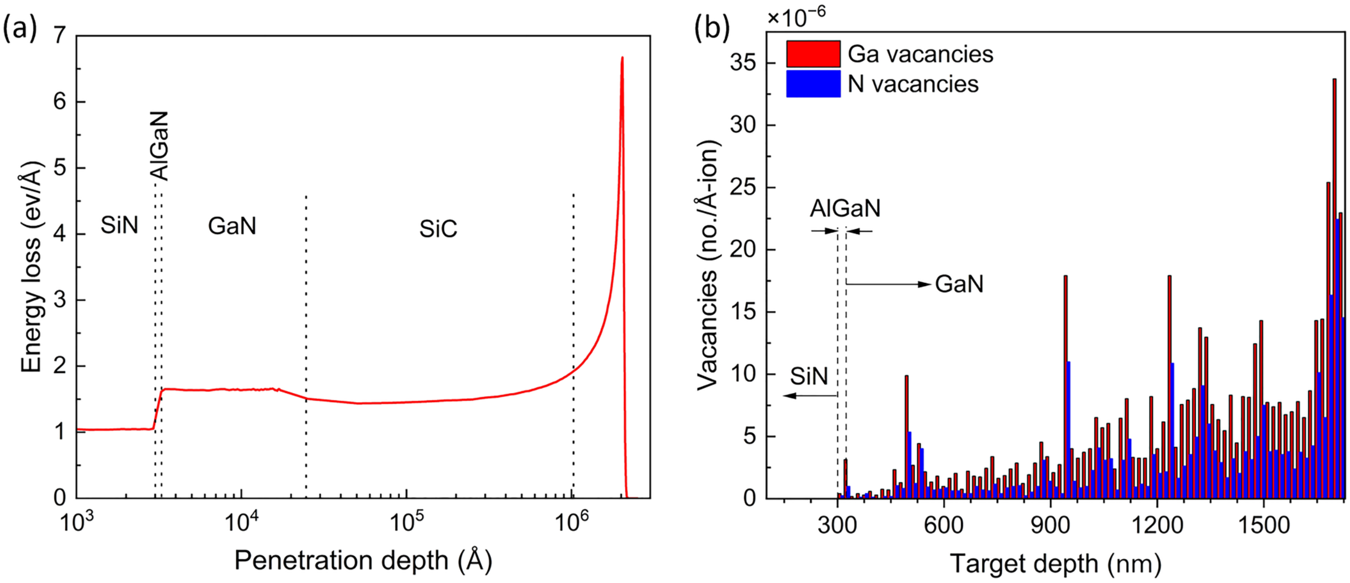

FIG. 2. SRIM simulation results showing (a) total energy loss and (b) gallium and nitrogen vacancy distribution by 5 MeV proton as a function of penetration depth into the AlGaN/GaN heterostructure.

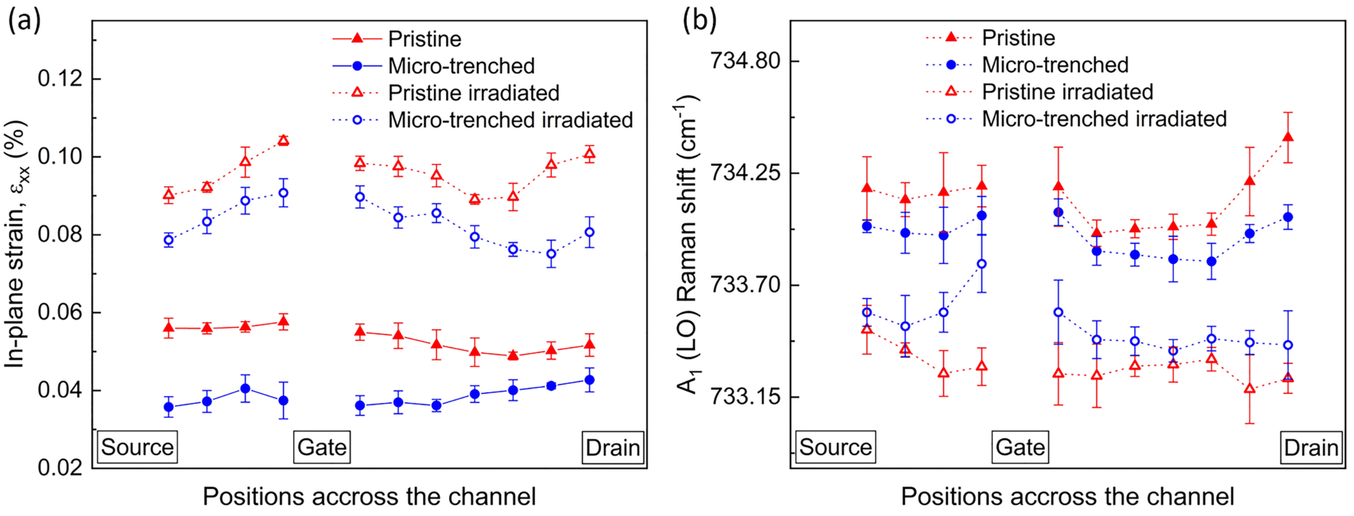

FIG. 3. Micro-Raman results across the device channel showing (a) in-plane strain distribution and (b) A_1 (LO) phonon peak position of the pristine and micro-trenched devices (at the location of strain relief) before and after proton irradiation.

vary from 049 ± 0.001% to 0.057 ± 0.002% across the channel from source to drain regions. The micro-trenched devices demonstrate a relaxation of tensile strain at the vicinity of the trench because of partial removal of the substrate, and the corresponding ε_{xx} values vary from 0.036 ± 0.002% to 0.042 ± 0.003%. After proton irradiation, the in-plane strain of both devices increases. The ε_{xx} values of the pristine and micro-trenched devices are found to vary from 0.089 ± 0.003% to 0.1 ± 0.002% and 0.075 ± 0.003% to 0.091 ± 0.003%, respectively. The post-irradiation strain distribution reveals the presence of higher strain at the gate and drain edges of the channel for both devices. The initial higher values of the strain of the pristine devices led to post-irradiation higher strain distribution compared to the micro-trenched devices. We observed approximately 0.3–0.4 and 0.5–0.6 cm^{-1} red shift of the SiC substrate TO and LO phonon modes, respectively. This red shift of SiC Raman peaks represents the increase of the strain level of the SiC substrate itself, which can translate into the GaN layer increasing its strain. However, several studies in the literature, involving the sapphire substrate, observed no change in the post-irradiation strain in GaN.[59–61] Such a discrepancy could be attributed to the difference in the initial strain/defect level, substrate materials, irradiation energy, and fluence. To study the contribution of different materials, we performed SRIM simulation of SiC and sapphire substrates, keeping all other parameters the same. The penetration depth and energy loss for SiC were found to be 200 μm and 6.5 eV/Å, respectively [Fig. 2(a)]. Corresponding values for sapphire were 240 μm and 5.5 eV/Å. We suggest that the higher stopping power of SiC could explain why we observed higher pos-irradiation strain compared to the studies using sapphire.

The frequency distribution of the GaN A_1 (LO) Raman peak before and after irradiation is shown in Fig. 3(b). The frequency of the A_1 (LO) peak of the pristine devices is found to be higher compared to the micro-trenched devices before proton irradiation, suggesting higher free carrier concentration of the pristine devices according to the theory of coupled plasmon A_1 (LO) phonon mode.[62,63] After irradiation, the A_1 (LO) phonon frequency of both devices shifts toward a lower wavenumber indicating the reduction of free carrier concentration due to proton irradiation. However, intriguingly, the A_1 (LO) phonon frequency of the micro-trenched devices at the trenched location is found to be relatively higher compared to the pristine devices after irradiation, which implies that the reduction of free carrier concentration due to proton irradiation in the micro-trenched region is less severe compared to the pristine counterpart. After proton irradiation, the FWHM values of the E_2 (high) and A_1 (LO) peaks for the pristine devices increase from 2.52 ± 0.1 to 2.97 ± 0.14 and 6.17 ± 0.18–6.91 ± 0.12 cm^{-1}, respectively. In the case of the micro-trenched devices, the FWHM values of the E_2 (high) and A_1 (LO) peaks increase from 2.63 ± 0.06 to 2.95 ± 0.11 and 6.26 ± 0.15–6.69 ± 0.09 cm^{-1}, respectively. The broadening of Raman peaks after proton irradiation indicates the increased defect density in the GaN layer, which could contribute to the degradation of electrical properties by increasing the trap density in the device. The slightly narrower A_1 (LO) peak of the irradiated micro-trenched devices compared to the irradiated pristine devices suggests relatively lower defect density, which could reduce the proton irradiation induced degradation of electrical properties of the micro-trenched devices.

The output characteristic curves (I_{ds}–V_{ds}) and the transfer curves (I_{ds}–V_{gs}) of the pristine and micro-trenched devices before proton irradiation are shown in Figs. 4(a) and 4(b), respectively. The micro-trenched devices show higher ON-resistance (R_{ON}), which is the reciprocal of the slope of I_{ds}–V_{ds} curves, compared to the pristine devices. The ON-resistances of the pristine and micro-trenched devices are calculated to be 3.7 and 4.28 Ω, respectively, at zero gate voltage ($V_{gs} = 0$ V). The saturation drain current ($I_{ds,sat}$) of the micro-trenched devices is also found to be smaller compared

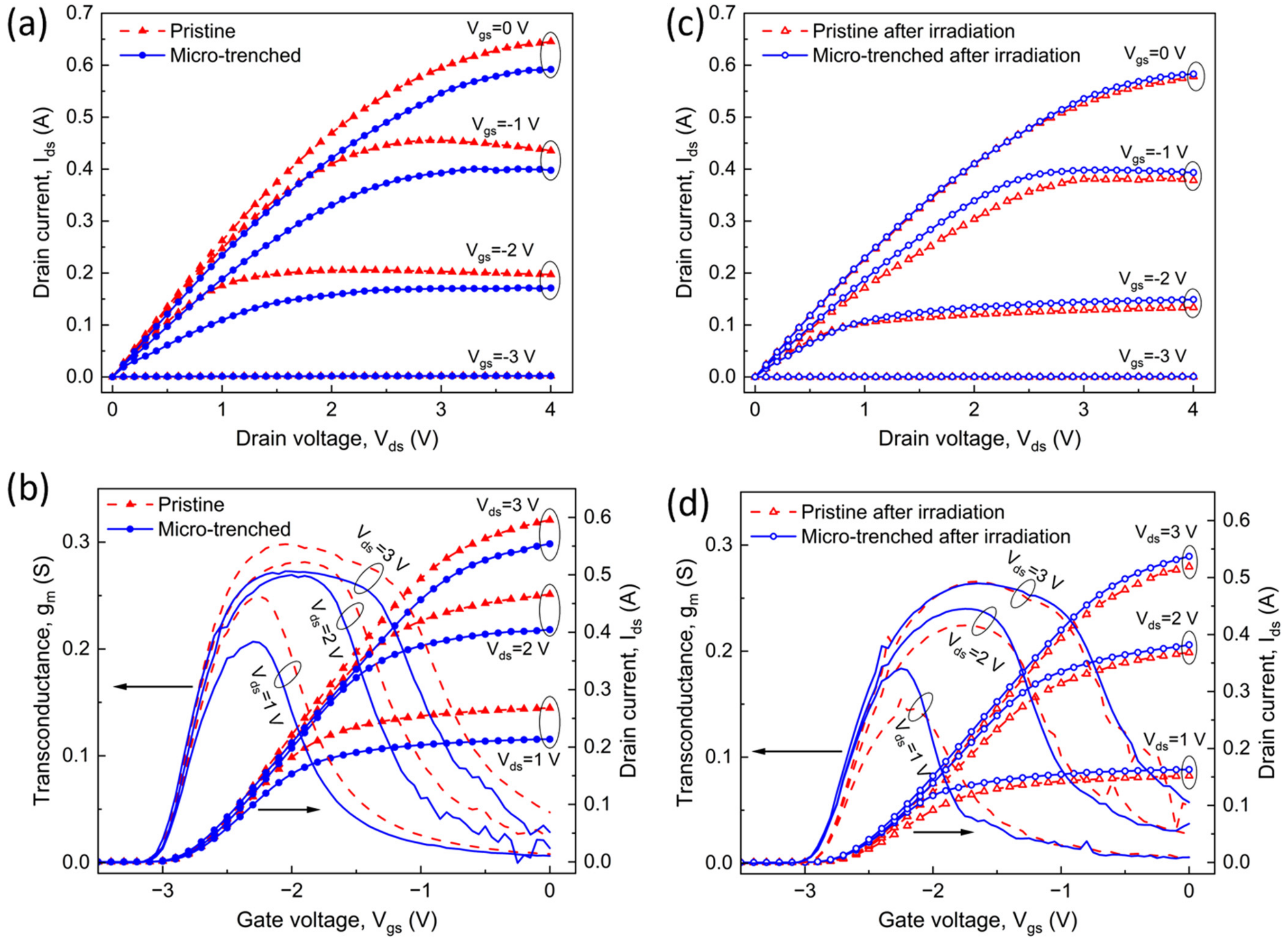

FIG. 4. Transport characteristics of the pristine and micro-trenched devices showing (a) output curves and (b) transfer curves before radiation, and (c) output curves and (d) transfer curves after radiation.

to the pristine devices. The higher R_{ON} and smaller $I_{ds,sat}$ of the micro-trenched devices is the result of partial relief of in-plane strain in the GaN layer, as shown in Fig. 3(a), at the middle of each channel of the six-channel device. The partial relaxation of the strain also reduces the transconductance of the devices, as shown in Fig. 4(b). However, such partial relaxation of strain does not change the threshold voltage (V_{th}) of the devices, which is found to be −3 V for both devices. The output characteristics and the transfer curves of the devices after proton irradiation are presented in Figs. 4(c) and 4(d), respectively. Noticeable increases of R_{ON} and reduction I_{dssat} are observed for both devices after irradiation. Both of the devices experience a positive shift of threshold voltage, which results from negatively charged traps in the AlGaN barrier layer and/or the GaN buffer layer.[11] The threshold voltage of the pristine and micro-trenched device shifts to −2.85 and −2.92 V, respectively. The maximum transconductance (G_M) of the devices also decreased after proton irradiation. Proton irradiation displaces atoms from the AlGaN and GaN layer creating nitrogen interstitials and gallium–nitrogen divacancies. These defects act as acceptor like traps in the AlGaN/GaN 2DEG interface causing a positive shift of threshold voltage and reduction of transconductance.[11,64]

The relative change of drain saturation current ($\Delta I_{ds,sat}$), ON-resistance (ΔR_{ON}), and maximum transconductance (ΔG_m) for different gate and drain bias conditions of the pristine and localized strain relieved devices are represented in Figs. 5(a) and 5(b). The reduction of $I_{ds,sat}$ and increase of R_{ON} values of the pristine devices are relatively larger compared to the micro-trenched devices, as shown in Fig. 5(a). At a gate voltage of −2 to 0 V, the proton irradiation causes ∼32%–10% reduction of $I_{ds,sat}$ for the pristine devices, whereas, the reduction of $I_{ds,sat}$ for the micro-trenched devices is only ∼13%–2%. The relative increase of R_{ON} at a gate voltage of −2 to 0 V for the pristine and micro-trenched

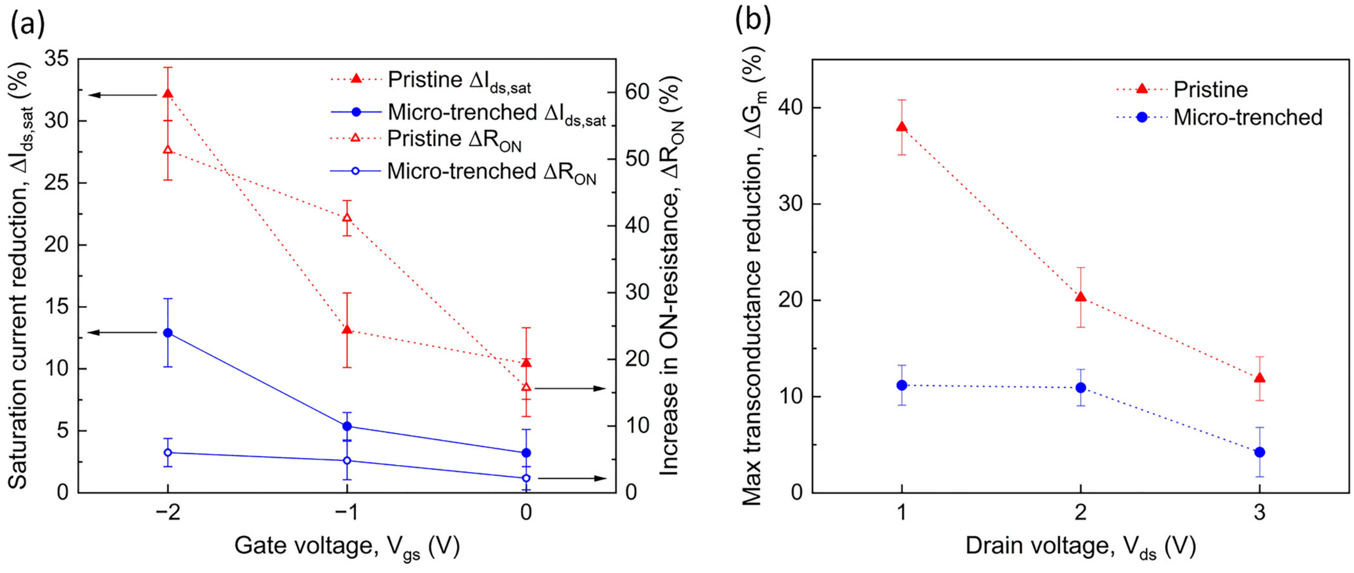

FIG. 5. Relative change of transport properties after proton irradiation showing (a) reduction of drain saturation current and increase of ON-resistance and (b) reduction of maximum transconductance.

devices is found to be ∼51%–15% and ∼6%–2%, respectively. Significant differences in maximum transconductance values are also observed after proton irradiation, as shown in Fig. 5(b). At a drain voltage of 1–3 V, the G_M values decrease by ∼38%–10% and ∼11%–3% for the pristine and micro-trenched devices, respectively.

The degraded transport properties of the devices after proton irradiation are attributed to the reduction of 2DEG sheet carrier density (n_s) and mobility (μ_n). The n_s and μ_n are estimated using the following equations from C–V measurements:[65,66]

$$n_s = \int_{V_{th}}^{V_{gs}} \frac{CdV}{Sq},$$

$$\mu_n = \frac{I_{ds}L_g}{qn_sW[V_{ds} - I_{ds}(R_D + R_S)]},$$

$$R_D = \frac{L_{gd}W}{qn_{s0}\mu_{n0}},$$

$$R_S = \frac{L_{gs}W}{qn_{s0}\mu_{n0}},$$

where S is the Schottky contact area, q is the electron charge, I_{ds} is the drain to source current at drain to source voltage of $V_{ds} = 0.1$ V, W is the gate width, L_g is the gate length, L_{gd} is the gate to drain distance, L_{gs} is the gate to source voltage, and n_{s0} and μ_{n0} are the electron density and mobility at zero gate bias, respectively. The effect of proton irradiation on the relative change of sheet carrier density (Δn_s) and mobility ($\Delta \mu_n$) is presented in Figs. 6(a) and 6(b), respectively. The carrier density and mobility of both devices decrease after proton irradiation. This could be attributed to radiation induced defects such as gallium and nitrogen vacancies and interstitials. Dislocations and cracks can also be generated after proton irradiation. In addition, the strain in the GaN layer after irradiation for both devices is found to be higher compared to the pristine devices, as shown in Fig. 3(a). Higher tensile strain in the GaN layer could produce relaxation of strain in the AlGaN layer and AlGaN/GaN interface, which can nucleate defects and trap centers for electrons during operation reducing the mobility.[67,68] However, the degradation of the micro-trenched devices is far less severe compared to the pristine devices. The carrier density of the pristine and micro-trenched devices drops by ∼15%–5% and ∼9%–3%, respectively, for the gate voltage of −2 to 0 V, which agrees with the results obtained by the Raman experiment, as shown in Fig. 3(b), by higher A_1 (LO) phonon frequency of the micro-trenched devices compared to the pristine devices after irradiation. The reduction of mobility for the pristine devices is found to be ∼48%–22%, whereas the corresponding value for the micro-trenched devices is only ∼30%–4%. The displacement defects such as vacancies created by proton irradiation act as the charged trap centers within the bandgap. These trap centers capture the free carriers reducing the carrier concentration of the 2DEG.[20,34] The lattice defects also act as the scattering centers for electrons reducing the mobility.[18,19,69] In addition, proton irradiation is reported to increase the AlGaN/GaN interface roughness, which further increases the scattering of 2DEG electrons reducing the mobility of the device.[13,24] One important aspect of proton irradiation induced damage of both devices is that the gate voltage of the devices plays an important role in the degradation of transport properties, as can be seen in Figs. 5 and 6. The closer the gate voltage is to the

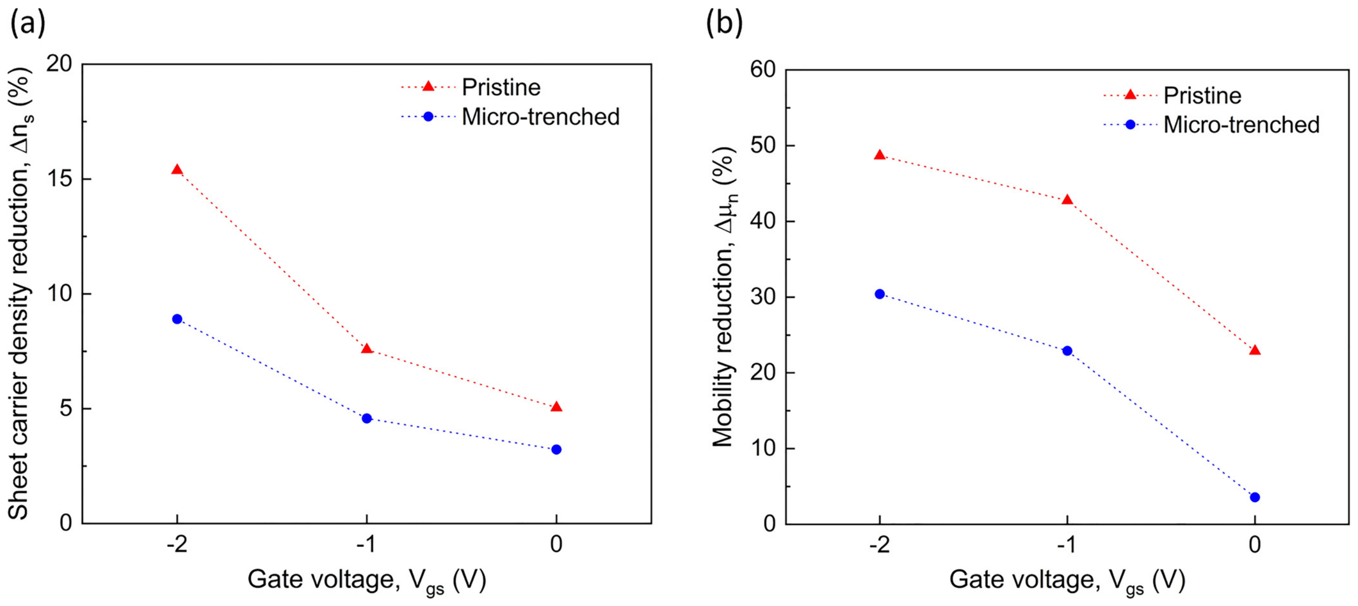

FIG. 6. Relative change of (a) sheet carrier density and (b) mobility of the pristine and micro-trenched devices after proton irradiation.

threshold voltage of the device, the higher the degradation, which might be due to the higher electric field associated with higher reverse bias. The higher electric field generates larger inverse-piezoelectric stress causing a strain relaxation in the AlGaN and GaN layers and creates electrically active crystal defects.[70]

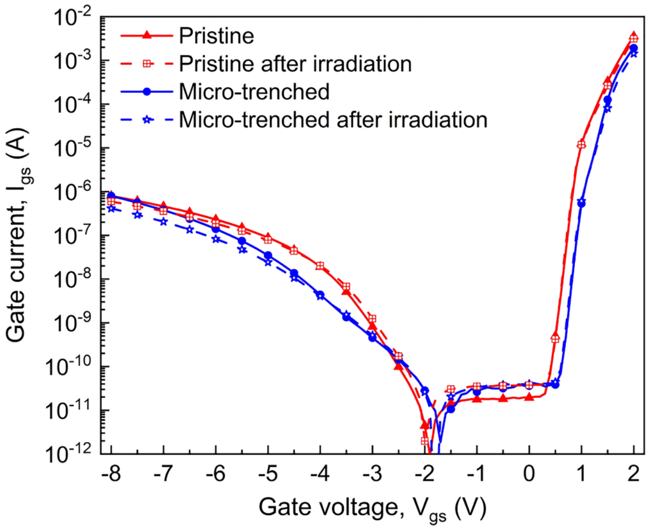

FIG. 7. Gate leakage current of the pristine and micro-trenched devices before and after proton irradiation.

The gate leakage currents of the pristine and micro-trenched devices before and after irradiation are shown in Fig. 7. After proton irradiation, the leakage current of both devices reduces slightly. The reduction of the gate leakage current could be due to the formation of the interfacial oxide layer, defects, and voids generated under the metal Schottky contact reducing the effective gate area.[18,28,29] However, the reduction of the gate leakage current of the pristine devices is relatively smaller compared to the micro-trenched devices, which may be associated with the higher strain relaxation in the AlGaN barrier of the pristine devices compared to the micro-trenched devices leading to carrier tunneling and higher gate leakage.

Overall, the localized strain relaxed micro-trenched devices exhibit better radiation hardness compared to the pristine devices as demonstrated by a smaller reduction of drain saturation current, maximum transconductance, 2DEG carrier concentrations, and mobility along with smaller positive threshold voltage shifts and lower gate leakage current. Li *et al.*[48] reported that higher tensile strain in the GaN reduces its threshold displacement energy, which is inversely proportional to the defect density of the material. Relatively smaller tensile strain in the micro-trenched devices causes a smaller change in threshold displacement energy compared to the highly strained pristine device. As a result, the micro-trenched devices have smaller defect density after irradiation compared to the pristine counterparts, resulting in lower trap concentration and/or electrically active defects. In addition, localized strain relaxation of the micro-trenched devices is expected to induce smaller inverse-piezoelectric stress and thermoelastic stress along the channel,[36] which might reduce the scattering of electrons during operation leading to higher mobility, drain saturation current, and transconductance compared to the irradiated pristine devices.

CONCLUSIONS

While the effect of strain and proton irradiation on AlGaN/GaN HEMTs has been studied separately in the existing literature, their combined effects on the performance of GaN HEMTs have not been studied previously. Here, we investigate the proton irradiation induced degradation of AlGaN/GaN HEMTs in the presence of localized strain relaxation, which is achieved by the micro-trenching technique. The 5 MeV proton irradiation at a fluence of $5 \times 10^{14}\,\text{cm}^{-2}$ causes additional strain in the GaN layer, which is initially under tensile strain. Although the local relaxation of tensile strain is found to reduce the drain output current and transconductance of the devices before irradiation, the post-irradiation properties are less susceptible to radiation damage compared to the pristine devices. The strain relieved devices show relatively smaller positive threshold voltage shifts after proton irradiation compared to the pristine devices. The degradation of the transport properties such as drain saturation current, maximum transconductance, sheet carrier density, and mobility of the strain relaxed micro-trenched devices is noticeably less severe compared to pristine devices. Relatively less susceptibility of proton irradiation damage for the localized strain relaxed devices compared to the pristine devices could be attributed to the smaller change in threshold displacement energy, smaller operation related stress such as inverse-piezoelectric stress and thermal stress leading to lower defect concentration and scattering of electrons during operation. Therefore, the relaxation of strain of AlGaN/GaN HEMTs could be advantageous to alleviate the proton irradiation induced degradation to some extent.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Nahid Sultan Al-Mamun: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal). **Joonyup Bae:** Formal analysis (equal); Investigation (equal); Methodology (equal). **Jihyun Kim:** Investigation (equal); Methodology (equal); Supervision (equal); Writing – review & editing (equal). **Aman Haque:** Conceptualization (equal); Data curation (equal); Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal). **Douglas E. Wolfe:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **Fan Ren:** Conceptualization (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – review & editing (equal). **Stephen Pearton:** Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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