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Nanoscale Stress Localization Effects on the Radiation Susceptibility of GaN High-Mobility Transistors

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Nanoscale localized mechanical stress fields develop unavoidably in microelectronic devices due to structural and processing aspects. Their global average is too small to influence bandgap or mobility, but it is proposed that stress localization can influence defect nucleation sites under radiation. This is investigated on gallium nitride high-electron-mobility transistors (GaN HEMTs). Using transmission electron microscopy, we spatially resolved the stress field in the AlGaN layer for both pristine and 10 Mrad gamma-irradiated HEMTs. The quantitative nanobeam electron diffraction and geometric phase analysis indicate that tensile stressed localizations experience higher radiation-induced strain. This finding is explained by the tensile stress dependence of the carrier concentration and mobility in the AlGaN layer. Since gamma radiation damage is inflicted by high-energy electrons only, localized regions of higher tensile stress in the AlGaN layer are expected to be more susceptible to gamma rays.

1. Introduction

Mechanical stress effects on microelectronics have been studied for decades to enhance transport properties in silicon technologies.[1] In high-electron-mobility transistors (HEMTs), a high-density 2D electron gas (2-DEG) is generated by a uniform mechanical stress field. Such unique channel characteristics give rise to low on-resistance and high-frequency behavior without any intentional doping.[2,3] Due to their wide bandgap, high critical field, and good saturation velocity, GaN HEMTs are more attractive for high-frequency, high-power applications.[3,4] High threshold energy (E_d) for atomic displacement,[5] dynamic annealing of point defects,[6] and absence of a conventional gate insulator[7] make them attractive in radiation environment as well.

The intentionally induced stress field in the GaN HEMT is mostly uniform throughout the channel. This could be a reason why the concept of localized stress is yet to be investigated in the literature. The other reason could be the small global average of the localized stresses; which may appear too insignificant to influence any properties. Finally, mapping mechanical stress with nanoscale resolution is a daunting task. All these factors compounded the GaN HEMT literature to study the role of the uniform stress field only. However, off-state biasing may induce highly localized mechanical stress around the electrical field.[8] Device fabrication and design features can also create stress localization. However, there is no concerted effort to map spatial non-uniformity of mechanical stress to investigate the effects on transistor characteristics. The commonly applied experimental techniques, such as cantilever,[9] three-,[10] and four-[11] point bending cannot capture stress localization. Substrate removal[12,13] is also used to generate uniform bending stress.

The motivation for this study comes from the opportunities offered by stress confinement effects to identify regions susceptible to radiation. We hypothesize that nanoscale confined stresses (mechanical hotspots) may dictate site-specific nucleation of radiation damage (or even operational degradation). For example, gate leakage of HEMTs has been ascribed to the local stress intensity that promotes interdiffusion of the Schottky contact metallization.[14] Only a few studies have attempted to control intrinsic stress to show appreciable influence over radiation effects.[15,16] There is a need to extend these studies to specific types of radiation and stress.

2. Experimental Results and Discussion

TEM images in **Figure 1** show a significant amount of displacement damage leading to dislocation threads in a 10 Mrad gamma-irradiated HEMT. This is indicated in the dashed rectangle in a low magnification mode. Higher magnification observation in the same areas indicates reduced periodicity in the lattice,

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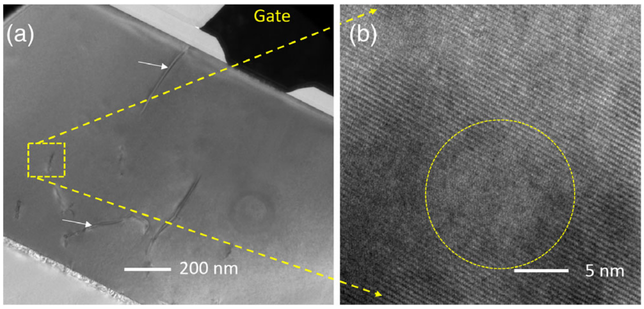

Figure 1. a) Displacement damage in 10 Mrad gamma-irradiated gallium nitride high-electron-mobility transistors (GaN HEMT). The arrows indicate line defects or dislocations. b) High-resolution transmission electron microscope (TEM) (dashed circle) shows an example of localized areas with reduced crystallinity.

shown with a dashed circle. Similar lattice damage was observed in the AlGaN layer as well. Such displacement damage resulted in a ≈16% decrease in saturation current in the device and a ≈6% decrease in transconductance.[17] Leakage current was most adversely affected, with an increase of ≈3 orders of magnitude. The details on the degradation of electrical characteristics are given in **Figure 2**.

While lower doses of gamma irradiation are known to enhance performance,[18,19] doses exceeding one are expected to show permanent degradation. This is clearly observed in the measured electrical characteristics in Figure 2. The extent of damage depends on the dose rate as well. It is possible that our dose rate of 180 krad h^{-1} did not allow enough time for the relatively mobile nitrogen vacancies to self-anneal at low temperatures.[20] Gamma radiation generates high-energy electrons through the Compton scattering process, which create Frenkel pairs and defect clusters that can migrate, recombine, or form complexes.[21–23] The damage process, therefore, depends on the electron concentration and mobility in the material. The HEMT is a unique structure with AlGaN and GaN layers that are different in terms of carrier concentration. The AlGaN layer stress is always tensile in nature, which creates the 2-DEG near the AlGaN– GaN interface. The 2-DEG is essentially an extremely high concentration free-electron layer. If there is a nanoscale localization of higher tensile stress, that region may see excess free electrons, thereby increasing the gamma radiation susceptibility.

Figure 3 shows the mechanical stress mapping of the pristine and 10 MRad gamma-irradiated GaN HEMT at unbiased conditions. The strain $[(a_{\text{AlGaN}} - a_{\text{Ref. AlGaN}})/a_{\text{Ref. AlGaN}}]$ values are measured at the AlGaN layer only, hence they are all tensile in nature. For an Al concentration of 22%, the lattice parameters a and c for reference/relaxed AlGaN are calculated from Vegard's law.[24] We measured the strain of both in and out-of-plane directions and observe that the average in-plane strain value is higher than the out-of-plane as a result of lattice mismatch. We also noticed a higher gradient of strain near the device terminals in post-irradiation condition. Since localized strain is superimposed on the uniform polarization strain, our hypothesis suggests higher post-radiation strain in the localized region of tensile stress. This trend is observed in Figure 3.

We present an alternative approach to investigating our hypothesis. It is based on the observation that interfaces in multi-layers or heterostructures are intrinsically strained by lattice mismatch.[25] Interfaces are defined as 2D features with most of the atoms positioned at nonequilibrium inter-atomic distance. This is well-established in the HEMT literature through the abundance and prominence of traps in the AlGaN–GaN or GaN–barrier interfaces, albeit studied from an electronic transport perspective.[26] These traps are essentially created from the relaxation of highly localized mechanical stress.[27] Therefore, validation of our hypothesis could take place through a careful observation of radiation-induced defect density at the interface

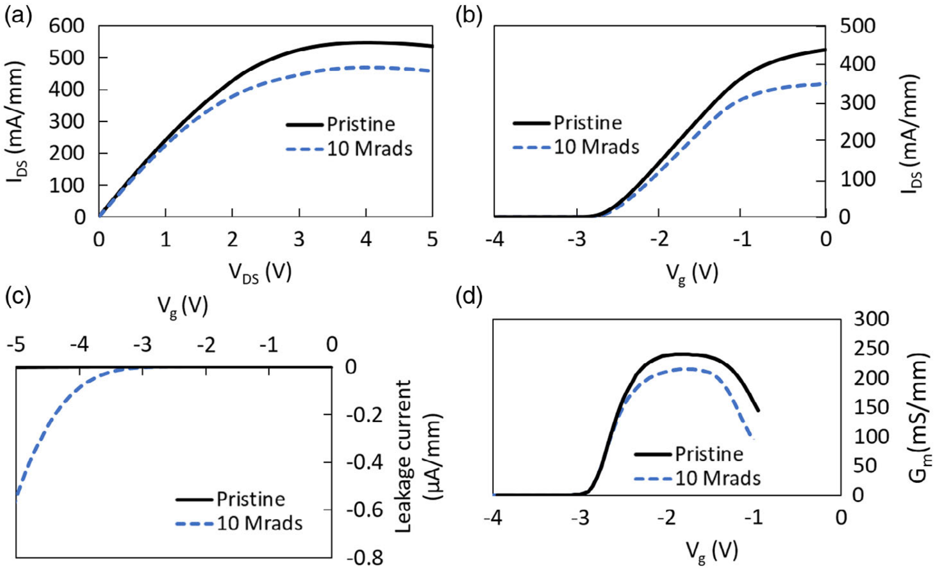

Figure 2. Effect of gamma irradiation on: a) output and b) transfer curves at zero gate voltage. c) Reverse characteristics as a function of gate voltage and d) transconductance–gate voltage curves as a function of gamma irradiation dose.

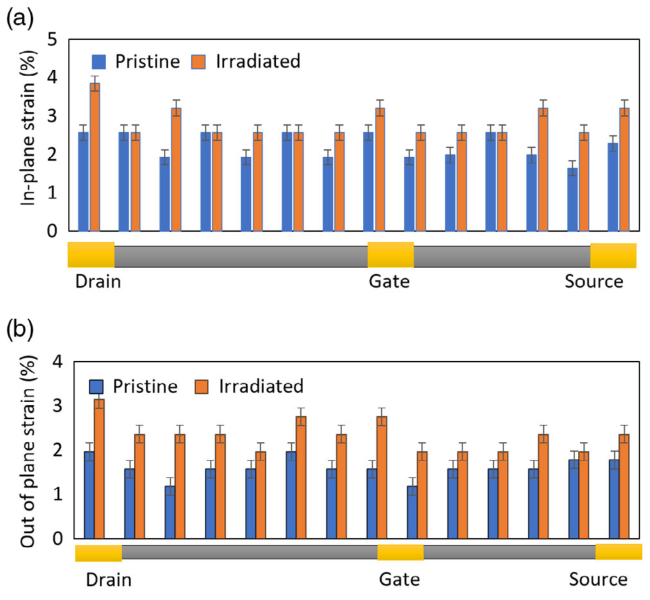

Figure 3. a) In-plane and b) out-of-plane strain mapping in the AlGaN layer along the channel of a 10 Mrad gamma-irradiated GaN HEMT.

and comparing that with the interior of the layers constituting the interface.

We mapped strain on both pristine and 10 Mrad gamma-irradiated HEMT specimens with nanoscale resolution. **Figure 4** shows TEM images of the AlGaN–GaN interface for pristine and irradiated specimens. To pinpoint the defects, we performed a geometric phase analysis.[28] This highlights the extent of radiation damage in atoms that are slightly away from equilibrium (at the interfaces indicated by the dashed lines) compared to the regular lattice in the AlGaN or GaN layers. We notice that both pristine and irradiated interfaces contain atomic defects. However, after irradiation, the AlGaN–GaN interface experiences significantly higher residual strain compared to the individual layers. This is shown in Figure 4b,d, where the strain scalebar read 1.5% in irradiated condition compared to 0.4% strain in pristine condition. Or in other words, the localized strain at the AlGaN–GaN interface makes it more susceptible compared to the individual layers. This qualitatively supports our hypothesis.

While this study is focused on the AlGaN layer, the fundamental concept of carrier concentration and mobility dependence of gamma radiation damage can be applied to the GaN layer. Here, there is not only no 2DEG—but also the stress field can be compressive. Compressive stress increases the electron's effective mass and decreases atomic binding energy (more rapidly than a tensile stress), making the GaN layer vulnerable to compression.[17] The stress measurement technique, therefore, plays a critical role. For example, Raman spectroscopy captures the GaN layer stress as the laser penetrates the surface passivation and ultra-thin AlGaN layer.[29] In contrast, cross-sectional specimens and nanobeam electron diffraction allow this study to probe the AlGaN layer only.

A final point of discussion is the relative contribution of the AlGaN and GaN layers to gamma radiation damage. Considering the very high penetrating capability of gamma rays, the AlGaN layer may see very little damage if it is facing the radiation source. Thus, the GaN layer, with more stopping power, could play a prominent role in permanent damage. This is clear from Figure 1, where dislocations are seen mainly in the GaN layer. It is also important to note that the fundamental mechanics of stress localization discussed in this study are applied only to gamma radiation.

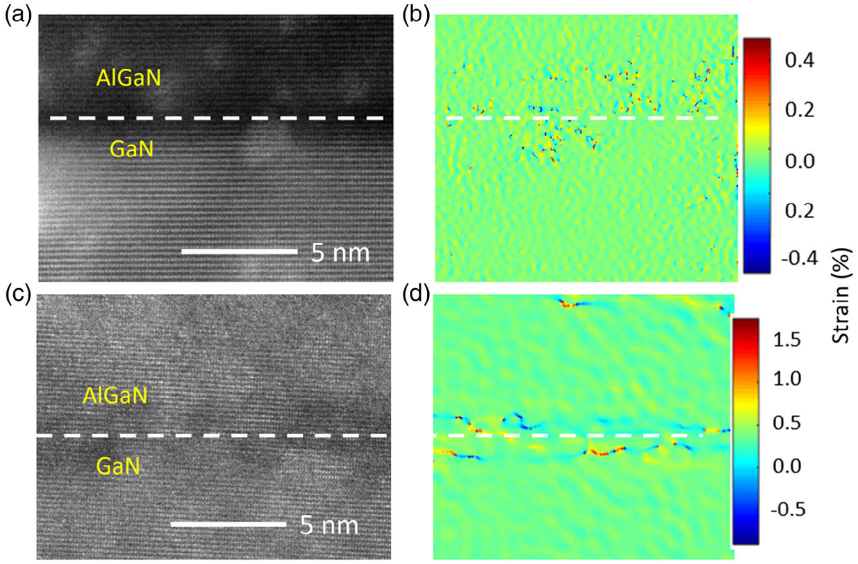

Figure 4. Bright field TEM image and geometric phase analysis mapping of the strain of the AlGaN–GaN interface for: a,b) pristine and c,d) exposed to 10 MRad gamma-irradiated conditions. Scale bar at the right (the value range of the scale bar is different for each image) highlights the extent of radiation damage strain at the interface compared to the bulk regions.

3. Conclusion

We propose that the radiation susceptibility of an electronic device is influenced by nanoscale stress concentrations, which arise due to materials synthesis, device architecture, and fabrication processing. Such localized stresses are mostly unavoidable consequences of fabrication and are different from the intentional strain engineering (e.g., forming the 2-DEG in a HEMT) that involves a uniform strain field. The effect of the stress is to increase carrier concentration and mobility, which influences radiation susceptibility. If validated, the hypothesis can help identify regions that are susceptible to radiation as well as operation degradation.

In this study, we performed nanobeam electron diffraction in the TEM on the AlGaN layer in both pristine and 10 Mrad gamma-irradiated HEMTs to investigate our hypothesis. The accuracy of the validation requires very precise strain mapping resolution over the entire device area. Therefore, a secondary (direct but qualitative) approach was undertaken. Here, the AlGaN–GaN interface was observed for the generation of atomic-scale structural defects in the irradiated HEMT compared to the pristine one. The preliminary results clearly show that the interface is affected more by the radiation compared to the individual AlGaN or GaN. This can be explained by the higher strain localization density at the interface. We conclude that insights into strain localization effects in electronics device degradation can lead to a fundamental understanding of spatial nonuniformity of irradiation or operation-related damage physics.

4. Experimental Section

Commercially available GaN HEMTs on SiC substrates (CGH60008D, Wolfspeed) were exposed to Cobalt-60 gamma radiation dose of up to 10 MRads at room temperature at grounded condition. This was performed at the Radiation Science and Engineering Center at Penn State University at a NIST traceable certified dose rate of 180 krad h^{-1}. The layer structure reported by the manufacturer included a ≈20 nm $Al_{0.22}Ga_{0.78}N$ barrier, ≈1 nm thick AlN interlayer, 1.4 μm GaN buffer, and 100 μm 4 H–SiC substrate with a gate length and width of $Lg = 0.25$ μm and $Wg = 200$ μm respectively. Electrical characterization is done after 4 h to avoid any short-term instability induced in the device by irradiation. The long-term stability of the device's electrical output was also checked and it was found that 10 Mrad irradiated devices showed no significant change over 3 months' period. Mechanical stress was spatially mapped on the ≈20 nm thick AlGaN layer, which typically experiences an in-plane biaxial stress. The nanobeam electron diffraction (NBED)[30] in a transmission electron microscope (TEM) was used. Electron transparent specimens were prepared with a Ga^{+} Focused Ion Beam (FIB), varying the ion beam current from 21 nA to 72 pA to minimize ion damage. NBED experiments were performed in a 200 kV FEI Talos F200X TEM with a 0.12 nm resolution. After aligning the samples to the zone axis ([1 0−1 0]), the smallest C2 aperture (10 μm) was used to make the beam size confined to the AlGaN layer.

The hypothesis was supported if the stress localized regions exhibit higher increments of irradiation-induced strain compared to other areas with no localization. It is well known that gamma rays produce high-energy electrons upon impingement. Therefore, higher electron concentration and mobility were expected to increase radiation susceptibility. Since the AlGaN layer exploits tensile stress to develop the 2-DEG, it was investigated whether the localized regions of high tensile stress also experience higher radiation damage.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

gallium nitride, gamma radiation effects, high-electron-mobility transistors, interface defects, mechanical stress concentration, transmission electron microscopy

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[1] G. Wang, in: *Engineering in 22 nm CMOS Technology Node and Beyond*, (Ed: G. Wang), Springer Singapore, Singapore **2019** p. 9.
[2] J. Tang, G. Liu, B. Mao, G. Zhao, J. Yang, *Rapid Res. Lett.* **2022**, *16*, 2100573.
[3] M. Meneghini, C. De Santi, I. Abid, M. Buffolo, M. Cioni, R. A. Khadar, L. Nela, N. Zagni, A. Chini, F. Medjdoub, G. Meneghesso, G. Verzellesi, E. Zanoni, E. Matioli, *J. Appl. Phys.* **2021**, *130*, 181101.
[4] J. He, W.-C. Cheng, Q. Wang, K. Cheng, H. Yu, Y. Chai, *Adv. Electron. Mater.* **2021**, *7*, 2001045.
[5] A. Ionascut-Nedelcescu, C. Carlone, A. Houdayer, H. J. V. Bardeleben, J. L. Cantin, S. Raymond, *IEEE Trans. Nucl. Sci.* **2002**, *49*, 2733.
[6] M. C. Sequeira, J.-G. Mattei, H. Vazquez, F. Djurabekova, K. Nordlund, I. Monnet, P. Mota-Santiago, P. Kluth, C. Grygiel, S. Zhang, E. Alves, K. Lorenz, *Comm. Phys.* **2021**, *4*, 51.
[7] D. M. Fleetwood, E. X. Zhang, R. D. Schrimpf, S. T. Pantelides, *IEEE Trans. Nucl. Sci.* **2022**, *62*, 1105.
[8] M. Li, S. Huang, X. Wang, F. Guo, Y. Yao, J. Shi, K. Wei, X. Liu, *Rapid Res. Lett.* **2022**, *16*, 2100539.
[9] B. S. Kang, S. Kim, J. Kim, F. Ren, K. Baik, S. J. Pearton, B. P. Gila, C. R. Abernathy, C. C. Pan, G. T. Chen, J. I. Chyi, V. Chandrasekaran, M. Sheplak, T. Nishida, S. N. G. Chu, *Appl. Phys. Lett.* **2003**, *83*, 4845.
[10] C. Chang, S. Hsiao, E. Y. Chang, C. Lu, J. Huang, C. Lee, *IEEE Electron Device Lett.* **2009**, *30*, 213.
[11] K. Liu, H. Zhu, S. Feng, L. Shi, Y. Zhang, C. Guo, *Microelectron. Reliab.* **2015**, *55*, 886.
[12] H. Zhu, X. Meng, X. Zheng, Y. Yang, S. Feng, Y. Zhang, C. Guo, *Solid-State Electron.* **2018**, *145*, 40.
[13] M. Azize, T. Palacios, *J. Appl. Phys.* **2010**, *108*, 023707.
[14] M. Broas, A. Graff, M. Simon-Najasek, D. Poppitz, F. Altmann, H. Jung, H. Blanck, *Microelectron. Reliab* **2016**, *64*, 541.

[15] N. N. Mahatme, B. L. Bhuva, Y. Fang, A. S. Oates, *IEEE Trans. Nucl.* **2012**, *59*, 845.
[16] M. Gaillardin, S. Girard, Y. Ouerdane, A. Boukenter, F. Andrieu, C. Tabone, O. Faynot, *J. Non-Cryst. Solids* **2011**, *357*, 1989.
[17] M. A. J. Rasel, S. P. Stepanoff, M. Wetherington, A. Haque, D. E. Wolfe, F. Ren, S. Pearton, *Appl. Phys. Lett.* **2022**, *120*, 124101.
[18] S. Pan, S. Feng, X. Li, X. Zheng, X. Lu, C. Hu, X. He, K. Bai, L. Zhou, Y. Zhang, *Semicond. Sci. Technol.* **2021**, *36*, 095011.
[19] J. Lee, E. Flitsiyan, L. Chernyak, J. Salzman, B. Meyler, *ECS J. Solid State Sci. Technol.* **2017**, *6*, S3063.
[20] G. A. Umana-Membreno, J. M. Dell, G. Parish, B. D. Nener, L. Faraone, S. Keller, U. K. Mishra, *J. Appl. Phys.* **2007**, *101*, 054511.
[21] J. H. Cahn, *J. Appl. Phys.* **1959**, *30*, 1310.
[22] I. Lyubomirsky, M. K. Rabinal, D. Cahen, *J. Appl. Phys.* **1997**, *81*, 6684.
[23] Q. Du, J. Michon, B. Li, D. Kita, D. Ma, H. Zuo, S. Yu, T. Gu, A. Agarwal, M. Li, J. Hu, *Photon. Res.* **2020**, *8*, 186.
[24] Z. Sheng-Qiang, W. Ming-Fang, Y. Shu-De, *Chin. Phys. Lett.* **2005**, *22*, 3189.
[25] M. J. Hÿtch, J. L. Putaux, J. Thibault, *Philos. Mag.* **2006**, *86*, 4641.
[26] E. Zanoni, M. Meneghini, A. Chini, D. Marcon, G. Meneghesso, *IEEE Trans. Electron Devices* **2013**, *60*, 3119.
[27] M. A. Mastro, J. R. LaRoche, N. D. Bassim, C. R. Eddy, *Microelectron. J.* **2005**, *36*, 705.
[28] S. Feng, Z. Xu, *Materials* **2021**, *14*, 4460.
[29] S. Choi, E. Heller, D. Dorsey, R. Vetury, S. Graham, *J. Appl. Phys.* **2013**, *113*, 093510.
[30] T. Grieb, F. F. Krause, M. Schowalter, D. Zillmann, R. Sellin, K. Müller-Caspary, C. Mahr, T. Mehrtens, D. Bimberg, A. Rosenauer, *Ultramicroscopy* **2018**, *190*, 45.