Applied Physics Letters

RESEARCH ARTICLE | JANUARY 03 2024

# Low temperature recovery of OFF-state stress induced degradation of AlGaN/GaN high electron mobility transistors

FREE

Nahid Sultan Al-Mamun ; Dina Sheyfer ; Wenjun Liu ; Aman Haque ; Douglas E. Wolfe ;
Darren C. Pagan



*Appl. Phys. Lett.* 124, 013507 (2024)
https://doi.org/10.1063/5.0179809

Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

# Low temperature recovery of OFF-state stress induced degradation of AlGaN/GaN high electron mobility transistors

Cite as: Appl. Phys. Lett. **124**, 013507 (2024); doi: 10.1063/5.0179809
Submitted: 4 October 2023 · Accepted: 9 December 2023 ·
Published Online: 3 January 2024



Nahid Sultan Al-Mamun,[1] Dina Sheyfer,[2] Wenjun Liu,[2] Aman Haque,[1,a)] Douglas E. Wolfe,[3] and Darren C. Pagan[3,a)]

## AFFILIATIONS

[1]Department of Mechanical Engineering, Penn State University, University Park, Pennsylvania 16802, USA
[2]X-ray Science Division, Argonne National Laboratory, Lemont, Illinois 60439, USA
[3]Department of Materials Science and Engineering, Penn State University, University Park, Pennsylvania 16802, USA

[a)]Authors to whom correspondence should be addressed: mah37@psu.edu and dcp5303@psu.edu



## ABSTRACT

Thermal annealing is a widely used strategy to enhance semiconductor device performance. However, the process is complex for multi-material multi-layered semiconductor devices, where thermoelastic stresses from lattice constant and thermal expansion coefficient mismatch may create more defects than those annealed. We propose an alternate low temperature annealing technique, which utilizes the electron wind force (EWF) induced by small duty cycle high density pulsed current. To demonstrate its effectiveness, we intentionally degrade AlGaN/GaN high electron mobility transistors (HEMTs) with accelerated OFF-state stressing to increase ON-resistance ∼182.08% and reduce drain saturation current ∼85.82% of pristine condition at a gate voltage of 0 V. We then performed the EWF annealing to recover the corresponding values back to ∼122.21% and ∼93.10%, respectively. The peak transconductance, degraded to ∼76.58% of pristine at the drain voltage of 3 V, was also recovered back to ∼92.38%. This recovery of previously degraded transport properties is attributed to approximately 80% recovery of carrier mobility, which occurs during EWF annealing. We performed synchrotron differential aperture x-ray microscopy measurements to correlate these annealing effects with the lattice structural changes. We found a reduction of lattice plane spacing of (001) planes and stress within the GaN layer under the gate region after EWF annealing, suggesting a corresponding decrease in defect density. Application of this low-temperature annealing technique for *in-operando* recovery of degraded electronic devices is discussed.



Gallium nitride (GaN) based electronic devices are promising due to their superior figure of merit and efficiency over current Si-based technology. However, despite exceptional electrical performance, GaN devices have yet to reach full potential and commercialization over concerns about electrical and structural reliability. AlGaN/GaN high electron mobility transistors (HEMTs) that manifest a sustained two-dimensional electron gas (2DEG), which provides exceptional mobility,[1,2] are one such attractive GaN-based device. However, they also suffer from residual and *in-operando* stress buildup due to lattice constant and thermal expansion coefficient mismatch of the epitaxial layers, in addition to inverse piezoelectric stresses that develop under high electric field.[3] The compounding effects of multiple contributions to stress trigger the nucleation of electrically active crystallographic defects that cause gradual degradation of electrical properties and even catastrophic failure.[3]

Electrical reliability testing of HEMTs is most often performed in the OFF-state,[3–16] semi-ON state,[17–20] or ON-state[5,6,10,14,16,21] configurations, each of which exhibits different degradation mechanisms. In the OFF-state, the reverse bias induced high electric field causes expansion of AlGaN by the inverse piezoelectric effect resulting in strain relaxation and lattice defects.[19] Also, the carriers collide with each other during high voltage operation generating energetic hot electrons, which get injected toward the barrier and passivation layer and get trapped creating interface states or bulk traps.[22] The semi-ON state degradation of GaN HEMTs is mostly caused by hot electrons.[17] ON-state degradation includes hot electrons and thermally activated trapping of electrons in the passivation layer and the semiconductor epilayers creating lattice defects.[10,23] Electrical degradation mechanisms and defect formation in different operating conditions and how to avoid such degradation by modifying the epitaxial structure and/or device configuration have been extensively reported, but there have been minimal studies of mitigation of defects and recovery of transport properties after degradation.

Thermal annealing is the most established technique to mitigate defects in semiconductor materials and devices. During thermal annealing, an increase in temperature increases the rate of motion of defects such as interstitials and vacancies. As a result, the defects can more readily diffuse to annihilate or escape. However, thermal annealing is not always conducive for multi-material multi-layered devices like HEMTs. Nonrecoverable degradation of GaN HEMT even after one day at 400 °C has been reported by Zhang *et al.*[24] Additionally, thermal annealing can potentially generate thermoelastic stresses due to the mismatch of thermal expansion coefficients that, in-turn, create defects and strain relaxation of the AlGaN layer leading to reduction of carrier concentration and mobility.[25–28] Moreover, high temperature defect mitigation technique can increase the interface roughness and potentially degrade the temperature sensitive gate Schottky and Ohmic contacts of the GaN HEMTs.[29,30]

Therefore, it is crucial to explore alternative non-thermal annealing to recover degradation of complex hetero-structured devices such as GaN HEMTs. Here, we exploit the use of high density pulsed current generated electron wind force (EWF) to recover electrical performance in degraded AlGaN/GaN HEMT devices at low temperature. The EWF originates from momentum transfer between electrons and defects. The EWF drives defect mobility when scattering electrons impart sufficient momentum leading to recombination of defects. Unlike thermal annealing, where thermal energy induced perturbation is random and distributed to the entire lattice, the EWF only acts upon lattice defects and is near-instantaneous. Therefore, minimal time is required for defects to annihilate if scattered by electrons with sufficient energy. EWF defect mitigation has been reported to be useful for irradiated GaN HEMTs,[31] thin film transistors,[32] two-dimensional field effect transistor,[33] and thin films.[34,35] However, the effectiveness of EWF on the recovery of electrically degraded GaN HEMTs is yet to be investigated.

In this research, commercially available depletion mode AlGaN/GaN HEMT devices (CGHV60008D, Wolfspeed®) were used. A cross section of the device, measured in the scanning electron microscope, is shown in Fig. 1(a). Electrical degradation of the devices was performed in the OFF-state condition by applying gate voltage ($V_{gs}$) of −5 V and drain voltage ($V_{ds}$) of 5 V for 48 h. Post stressing degradation recovery by EWF was performed with a current pulse generator Northrop Grumman eDrive™ Laser System Controller equipped with a Sorensen DCS 100-12E DC power supply. High density pulsed current was applied to degraded devices for 1 min using a pulse width of 20 $\mu$s and frequency of 2 Hz providing a duty cycle as low as 4%. This low duty cycle pulsed current suppressed temperature rise within the device despite the use of high-density current of $1.3 \times 10^4$ A/cm$^2$. An Optris PI-640 thermal microscope was used to monitor the real time temperature during EWF annealing, and a maximum temperature was recorded to be 30.1 °C, as shown in Fig. 1(b). All electrical characterization was performed on Cascade 1200 probe station equipped with Keithley 4200A-SCS semiconductor parameter analyzer at room temperature.

A recent work by Pagan *et al.* details the use of differential aperture x-ray microscopy (DAXM) to nondestructively measure residual stress in HEMTs.[36] DAXM is a synchrotron x-ray technique in which a focused x-ray beam (∼ sub-micron) and a differential aperture (100 $\mu$m diameter Pt scanning wire used as a knife-edge) are combined to isolate diffraction from sub-$\mu$m$^3$ volumes to determine local crystallographic orientation, lattice plane spacing (and elastic strain), or phase content. Here, DAXM was used to probe residual stresses in the GaN layer in HEMT devices in three different states: pristine, degraded, and EWF-annealed (see procedures above) at the 34-ID-E station of the Advanced Photon Source. A schematic of the measurement geometry is given in Fig. 1(c) with L and S describing the laboratory and sample coordinate systems, respectively. Rough positioning of the specimens was performed by using an optical camera aligned to the x-ray beam. To then align a transistor precisely to the incoming x-ray beam (dimensions 150 nm along $\boldsymbol{x}^L$ and 230 nm along $\boldsymbol{y}^L$), the illuminated

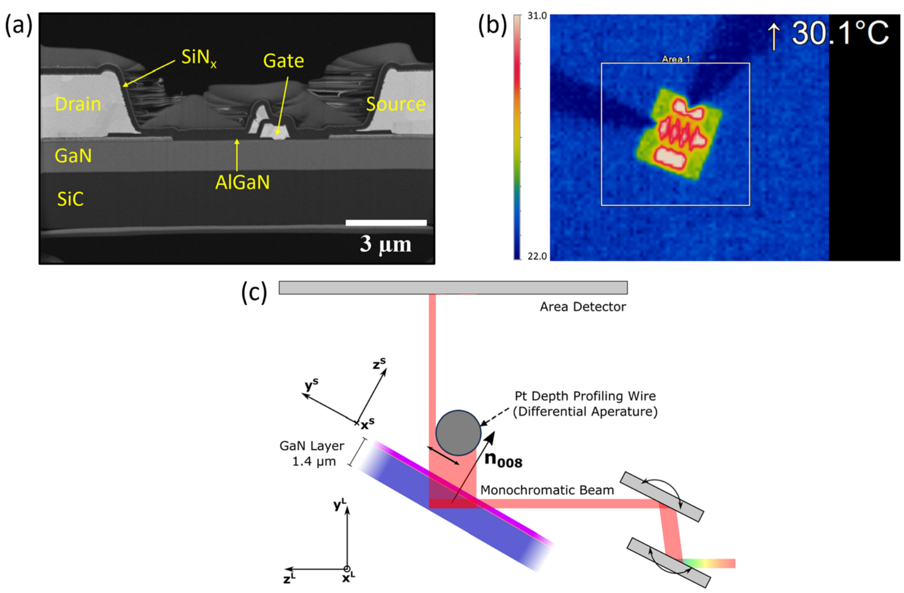


FIG. 1. (a) SEM cross section of the AlGaN/GaN HEMT. (b) Thermal microscopic image of the device during EWF annealing showing maximum temperature of the device. (c) Schematic of specimen and experimental geometry of DAXM.

specimen was translated while monitoring the L$\alpha$ characteristic fluorescence from the Au source, gate, and drain wires (see Fig. 4 for example fluorescence patterns). Finally, the crystallographic orientation of the GaN layer in the HEMT devices was determined by illuminating the specimen with a polychromatic x-ray beam and then indexing the resulting diffraction pattern on an amorphous silicon area detector (200 $\mu$m pixel size) placed 513 mm above the specimen using the LaueGo software package.

Once aligned and oriented, elastic strains were determined at each point by measuring the spacing $d$ of (008) lattice planes of the GaN layer [orientation in Fig. 1(c)]. The lattice plane spacing was determined by sweeping the energy of the incoming x-ray beam around 13.5 keV, where the Bragg diffraction condition is satisfied. The differential aperture moved with a step size of 0.5 $\mu$m along $\boldsymbol{y}^S$ repeatedly for depth resolving the diffraction signals. The specimen was then translated along $\boldsymbol{x}^S$ by every 1 $\mu$m. The strain $\varepsilon$ of the (008) lattice planes was then calculated from the shifts of $d$ spacing with respect to a reference (0.6483 Å), determined from an average of GaN c-axes lattice parameters reported in the literature.[37–39]

The DC output characteristics ($I_{ds}$–$V_{ds}$) of the pristine, degraded, and EWF-annealed devices are shown in Fig. 2(a). A decrease in drain current and current collapse are observed in degraded devices, which appear to be recovered partially after annealing using EWF. The EWF-annealed devices reach the drain saturation current ($I_{ds,sat}$) at relatively low $V_{ds}$ compared to the degraded devices. The extracted $I_{ds,sat}$ and ON-resistance ($R_{ON}$) values are presented with respect to applied $V_{gs}$ in Fig. 2(b). The $I_{ds,sat}$ of the degraded devices reduces to ~53.75%–85.82% of the pristine reference. The EWF annealing recovers the $I_{ds,sat}$ of the degraded devices up to ~83.59%–93.10% of pristine condition. The recovery of the devices by EWF annealing is also reflected in the $R_{ON}$ values. The $R_{ON}$ of the pristine devices increases to ~217.63%–182.08% of pristine condition after OFF-state stressing. After EWF annealing, the $R_{ON}$ is found to increase ~143.04%–122.21% of pristine condition, which suggests ~53.63%–67.12% decrease in $R_{ON}$ compared to the degraded devices. It is important to note that these values were obtained at DC biasing level lower than the operating regime of HEMTs. Low DC bias minimizes the influence of temperature since bare dies without proper packaging for heat removal were used in this study. Therefore, to maintain repeatability and accuracy of the reported results, we limited the drain bias of the devices up to 4 V. We believe the results obtained here would represent similar characteristics if tested at higher drain bias with proper thermal management system.

The transfer curves ($I_{ds}$–$V_{gs}$) along with corresponding transcendence curves ($g_m$–$V_{gs}$) at $V_{ds}$ of 1–3 V are shown in Fig. 2(c). The threshold voltage ($V_{th}$) of the pristine device appears to be unaffected by the OFF-state stressing. Similar impact of OFF-state stressing on $V_{th}$ has been reported in the literature.[6,40] The unchanged $V_{th}$ of the device indicates that the degradation of the device is athermal in nature and most likely is the result of vertical electric-field-induced lattice strain enhancement.[6] This lattice strain enhancement likely nucleates crystallographic defects, which are electrically active and could potentially act as trapping centers for carriers.

The $g_m$–$V_{gs}$ curves show significant reduction of transconductance values of the degraded devices. In general, the OFF-state stressing generates traps under the gate due to the high electric field, evidenced here by the drop of transconductance over the entire $V_{gs}$ range. Additionally, the reduction of peak transconductance ($G_M$) at a higher drain voltage suggests that the trapping location can extend to the drain access region under high drain bias condition increasing the $R_{ON}$ resistance of the device, as observed in Fig. 2(b). The $G_M$ values at low $V_{gs}$ are also found to be reduced significantly. The reduction of $G_M$ at low $V_{gs}$ indicates the presence of traps in the GaN buffer layer, which are mostly ionized at low $V_{gs}$.[6]



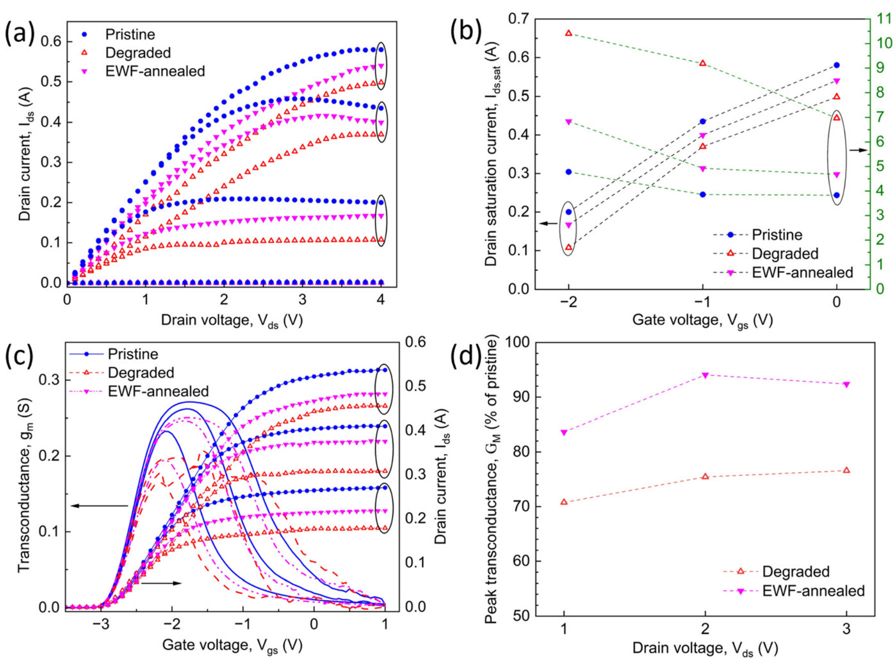


**FIG. 2.** (a) DC output curves ($I_{ds}$–$V_{ds}$) for $V_{gs}$ of $-3$–1 V, (b) extracted $I_{ds,sat}$ and $R_{ON}$, (c) transfer ($I_{ds}$–$V_{gs}$) and transconductance ($g_m$–$V_{gs}$) curves for $V_{ds}$ of 1–3 V, and (d) peak transconductance of degraded and EWF-annealed compared to pristine.

Importantly, a notable improvement in transconductance values is observed after annealing the degraded device with EWF. The recovery of transconductance is more pronounced at the peak, which is associated with the improvement of channel mobility.[40] The $G_M$ of the degraded and EWF-annealed devices compared to the pristine condition with respect to the applied $V_{ds}$ is presented in Fig. 2(d). The OFF-state stressing incurred a decrease in $G_M$ by ∼60.76%–76.58% of pristine, whereas the EWF-annealed devices recover $G_M$ up to ∼83.66%–92.38% of pristine condition.

To further investigate the GaN HEMTs degradation recovery efficacy of EWF annealing, we calculated the 2DEG carrier density ($n_s$) and mobility ($\mu_n$) by C–V measurements.[41,42] The $n_s$ and $\mu_n$ values of the degraded and EWF-annealed devices compared to the pristine condition corresponding to applied $V_{gs}$ are presented in Fig. 3(a). The OFF-state stressing appears to have very small impact on the carrier density of the GaN HEMT. However, OFF-state stressing results in a significant degradation of carrier mobility. The mobility of the degraded device is found to be ∼55.74%–62.91% of pristine after OFF-state stressing. The scattering of electrons by traps and crystal defects, generated during stressing, could be the dominant phenomena for reduced mobility. The annealing of the degraded device by EWF appears to have negligible effect on the carrier density, which is anticipated. The defect specificity nature of the EWF is only interactive with localized defects without perturbing the lattice atoms. Therefore, it only modifies the local strain field of the device leaving the global strain of the 2DEG interface unaffected resulting in inconsequential impact on the carrier density. Nonetheless, the EWF annealing demonstrates noticeable improvement of mobility, as shown in Fig. 3(a). Approximately 80% recovery of mobility is observed after EWF annealing of the degraded device.

The gate leakage currents of the devices are shown in Fig. 3(b). More than two orders of magnitude higher gate leakage currents are monitored in the degraded device compared to the pristine, which suggests permanent damage of the gate Schottky contact. The gate damage could include the formation of micro-pits or grooves under the gate contact and diffusion of metal elements into the barrier layer under the reverse bias induced high electric field leading to a leakage path for reverse current conduction.[43,44] Trap assisted tunneling could also contribute to the higher leakage current of the degraded device. The EWF annealing slightly reduces the gate leakage current, which might be due to mitigation of defects and traps under the gate. It is expected that the EWF does not recover the pits/cracks and diffusion of metal atoms, which are the dominant leakage path. As a result, the EWF annealing is mostly ineffective to recover the gate leakage current of the degraded device.

We note that the observed degradation of the GaN HEMTs due to OFF-state stressing was irreversible under light illumination and even after one week of resting period at room temperature. The OFF-state stressing could generate defects such as gallium vacancies, gallium-nitrogen divacancies, hydrogenated oxygen impurities, and nitrogen antisites,[45–48] which could act as trapping sites for electrons degrading the performance of the device. Upon the application of high density pulsed current, these defects are mobilized by the EWF due to transfer of momentum from scattered electrons. Repetitive application of EWF drives the defects out of the system or could cause recombination and/or migration of the defects. However, elucidating mitigation mechanisms of different types of defects by EWF requires molecular dynamic simulation coupled with the density functional theory. It can be assured that the degradation of the devices was permanent and resulted from the physical damage of the heterostructure. Therefore, the recovery of electrical transport properties of the degraded devices by EWF annealing is not the consequence of spontaneous room temperature annealing due to de-trapping of temporary trapped electrons. Rather, it is solely caused by defect–electron interaction with EWF coming from the high density pulsed current leading to the recovery of lattice defects.

To estimate the recovery of lattice defects, we mapped the lattice plane spacing (*d*-spacing) and corresponding stress within the GaN epitaxial layer using DAXM. The *d*-spacings of GaN (001) lattice plane (c-axis lattice parameter) are presented in Fig. 4. The *d*-spacing of GaN (001) planes for the pristine device is found to be larger under the source and drain edges [Fig. 4(a)], while the *d*-spacing of the GaN layer increases across the entire channel after OFF-state stressing [Fig. 4(b)]. A gradient of *d*-spacing exists across the depth of the GaN layer with larger values near the AlGaN/GaN 2DEG interface and smaller values near the GaN/substrate interface, which suggests that the GaN layer experiences higher stresses near the 2DEG interface during degradation. Importantly, the GaN (001) *d*-spacing of the EWF-annealed device [Fig. 4(c)] is relatively smaller in comparison with the degraded device [Fig. 4(b)]. The reduction of *d*-spacing is more pronounced under the gate contact and the gate to drain access region near the 2DEG interface.

The biaxial stress in the GaN layer is estimated using elastic strains calculated from a reference *d*-spacing of GaN, the anisotropic form of Hooke's law (single crystal moduli from Ref. 36), and a plane strain stress assumption. The estimated biaxial lattice stress in the GaN

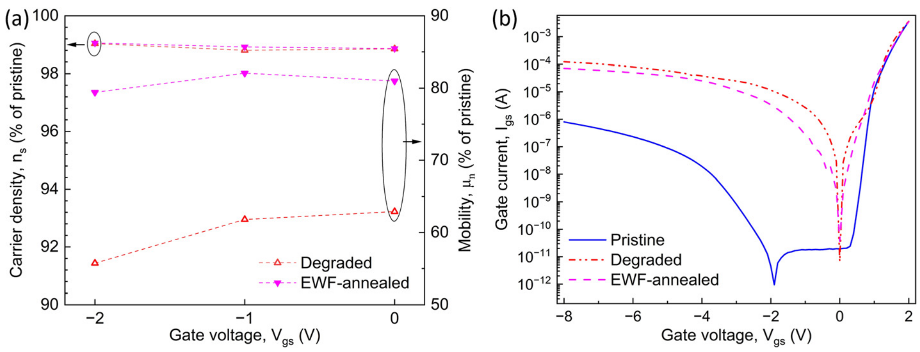


**FIG. 3.** (a) Carrier density and mobility of the degraded and EWF-annealed devices compared to pristine and (b) gate leakage currents.

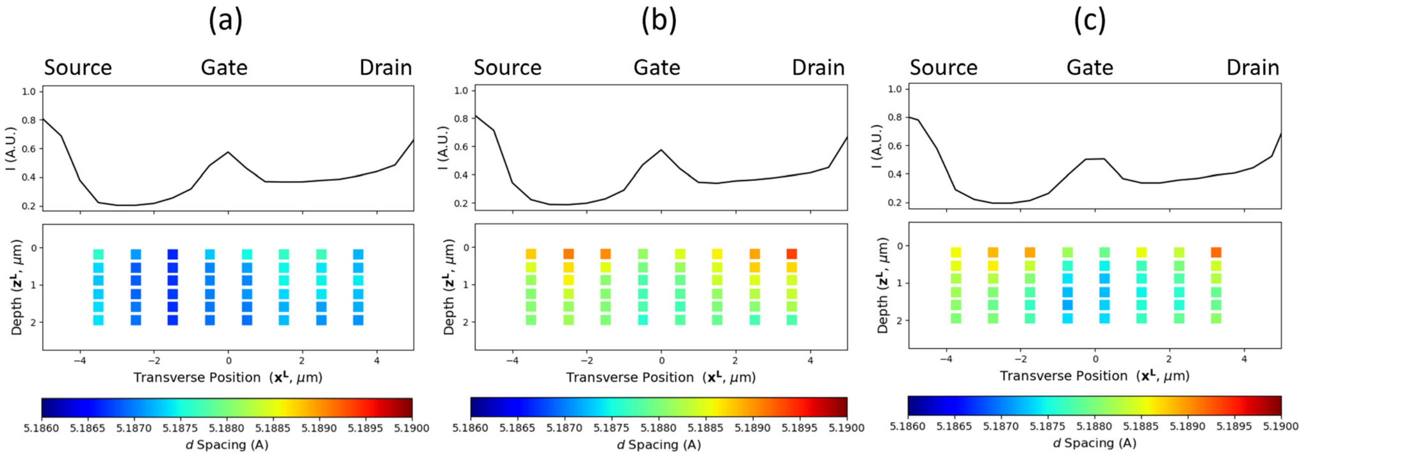


**FIG. 4.** Lattice plane space mapping of GaN (001) lattice plane (along the c axis) for (a) pristine, (b) degraded, and (c) EWF-annealed devices. The top figures represent the fluorescence intensity that has been used to determine the location of the source, gate, and drain contacts.

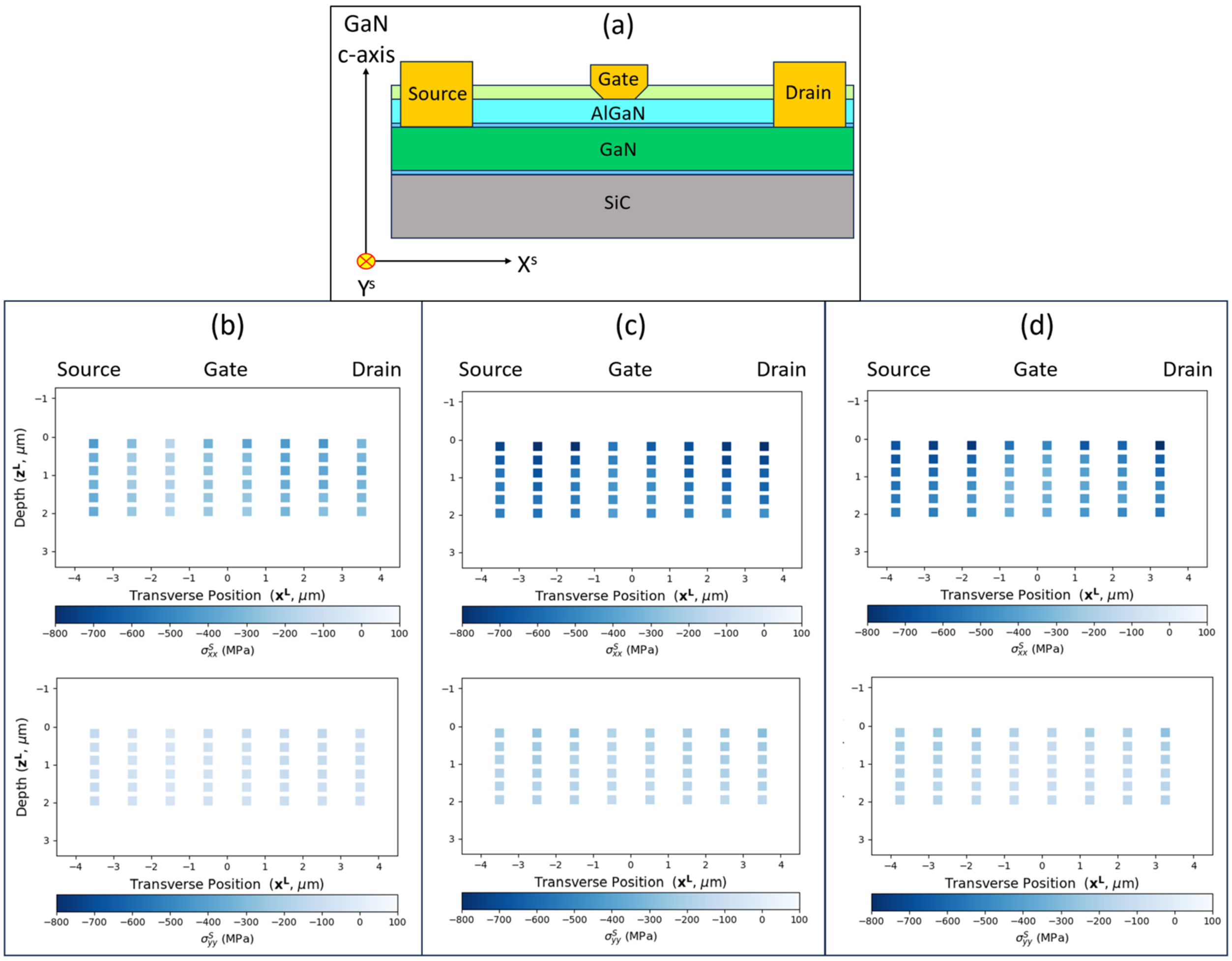


**FIG. 5.** The estimated stress components in the GaN epilayer. (a) The coordinates of the stress components. Stress across the channels ($\sigma^S_{xx}$) and along the channels ($\sigma^S_{yy}$) for (b) pristine, (c) degraded, and (d) EWF-annealed devices.

layer across the channels ($\sigma^S_{xx}$) and along the channels ($\sigma^S_{yy}$) in the sample coordinate system is presented in Fig. 5. The coordinates of the stress components are shown in Fig. 5(a). The $\sigma^S_{xx}$ values of the pristine device are found to be compressive in nature, whereas the $\sigma^S_{yy}$ component is found to be negligible [Fig. 5(b)]. It should be noted that the sign and magnitude of the stress are sensitive to the choice of reference *d*-spacing (see experimental procedure). The higher value of *d*-spacing results in a higher value of $\sigma^S_{xx}$ across the channel of the degraded device [Fig. 5(c)]. A subtle presence of $\sigma^S_{yy}$ as well is observed in the degraded device. The $\sigma^S_{xx}$ value of the EWF-annealed device is found to be lower compared to the degraded device, which is more prominent under the gate area [Fig. 5(d)]. Elastic distortion (or increase in stress or lattice strain magnitude) is generally observed in the vicinity of lattice defects.[49] The stress map of the EWF-annealed device indicates that the EWF annealing is most effective under the gate, where the *d*-spacings and stress magnitudes are reduced. The smaller stress magnitude of the EWF-annealed device compared to the degraded device also likely indicates relatively low density of defects and corroborates the recovery of electrical transport properties due to reduction in defects. Although the biaxial residual stress in the GaN layer of a similar device in the pristine state measured by micro-Raman has been previously reported to be tensile in contrast to these measurements,[50,51] the observed relative changes to stress with degradation and EWF annealing are more important for this work. We note that the cause of the difference in the sign of stress in comparison with the d-spacing in Fig. 4 is that the measured expansion of the c-axis is from Poisson expansion from the underlying compression biaxial stress state shown in Fig. 5.

Here, we demonstrated a rapid, low-temperature annealing technique utilizing EWF to recover the electrical transport properties of electrically degraded AlGaN/GaN HEMTs. The small duty cycle high density pulsed current induced EWF is found to be effective in recovering the electrical transport properties of the degraded HEMTs demonstrating recovery of up to ∼83.59%–93.10% and ∼83.66%–92.38% of $I_{ds,sat}$ and $G_M$ values, respectively, which were previously degraded to ∼53.75%–85.82% and ∼60.76%–76.58%, respectively, of the pristine condition along with a ∼53.63%–67.12% decrease in $R_{ON}$ of the degraded device. However, the EWF annealing is found to be unable to improve the gate leakage current. The *d*-spacing and residual stress mapping results obtained by DAXM measurements reveal that the EWF annealing decreases the *d*-spacing and lattice stress in the GaN layer, primarily under the gate. The reduced stress in the GaN layer suggests a reduction of defect density. The low temperature annealing technique could be conducive for practical applications to mitigate the defects of multi-layered multi-materials microelectronic devices, where conventional thermal annealing is potentially detrimental due to thermoelastic stress buildup, and useful for *in-operando* device recovery. In the future, to fully explore the potential of EWF annealing, different ON-state degradation mechanisms need to be examined along with a full mapping of EWF annealing duty cycles and current limits.

This work was funded by the Defense Threat Reduction Agency (DTRA) as a part of the Interaction of Ionizing Radiation with Matter University Research Alliance (IIRM-URA) under Contract No. HDTRA1-20-2-0002. A.H. also acknowledges support from the U.S. National Science Foundation (ECCS No. 2015795). The content of the information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred. Use of the Advanced Photon Source was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Nahid Sultan Al-Mamun:** Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal). **Dina Sheyfer:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Writing – review & editing (equal). **Wenjun Liu:** Data curation (equal); Investigation (equal); Methodology (equal); Resources (equal); Writing – review & editing (equal). **Aman Haque:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – review & editing (equal). **Doug Wolfe:** Investigation (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **Darren C. Pagan:** Conceptualization (equal); Data curation (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

## DATA AVAILABILITY

The data that support the findings of this study will be made available upon reasonable request.

## REFERENCES

[1] R. J. Trew, G. L. Bilbro, W. Kuang, Y. Liu, and H. Yin, "Microwave AlGaN/GaN HFETs," IEEE Microwave 6(1), 56–66 (2005).
[2] H. W. Jang, C. M. Jeon, K. H. Kim, J. K. Kim, S.-B. Bae, J.-H. Lee, J. W. Choi, and J.-L. Lee, "Mechanism of two-dimensional electron gas formation in $Al_xGa_{1-x}N$/GaN heterostructures," Appl. Phys. Lett. 81(7), 1249–1251 (2002).
[3] J. A. del Alamo and J. Joh, "GaN HEMT reliability," Microelectron. Reliab. 49(9), 1200–1206 (2009).
[4] M. Meneghini, A. Stocco, M. Bertin, D. Marcon, A. Chini, G. Meneghesso, and E. Zanoni, "Time-dependent degradation of AlGaN/GaN high electron mobility transistors under reverse bias," Appl. Phys. Lett. 100(3), 033505 (2012).
[5] E. A. Douglas, C. Y. Chang, D. J. Cheney, B. P. Gila, C. F. Lo, L. Lu, R. Holzworth, P. Whiting, K. Jones, G. D. Via, J. Kim, S. Jang, F. Ren, and S. J. Pearton, "AlGaN/GaN high electron mobility transistor degradation under on- and off-state stress," Microelectron. Reliab. 51(2), 207–211 (2011).
[6] M. Faqir, G. Verzellesi, G. Meneghesso, E. Zanoni, and F. Fantini, "Investigation of high-electric-field degradation effects in AlGaN/GaN HEMTs," IEEE Trans. Electron Devices 55(7), 1592–1602 (2008).
[7] F. Gao, S. C. Tan, J. Alamo, C. V. Thompson, and T. Palacios, "Impact of water-assisted electrochemical reactions on the OFF-state degradation of AlGaN/GaN HEMTs," IEEE Trans. Electron Devices 61(2), 437–444 (2014).
[8] R. Jiang, X. Shen, J. Chen, G. X. Duan, E. X. Zhang, D. M. Fleetwood, R. D. Schrimpf, S. W. Kaun, E. C. H. Kyle, J. S. Speck, and S. T. Pantelides, "Degradation and annealing effects caused by oxygen in AlGaN/GaN high electron mobility transistors," Appl. Phys. Lett. 109(2), 023511 (2016).

[9]J. Lin, H. Liu, S. Wang, C. Liu, M. Li, and L. Wu, "Effect of the high-temperature off-state stresses on the degradation of AlGaN/GaN HEMTs," Electronics **8**, 1339 (2019).
[10]G. Meneghesso, M. Meneghini, A. Stocco, D. Bisi, C. de Santi, I. Rossetto, A. Zanandrea, F. Rampazzo, and E. Zanoni, "Degradation of AlGaN/GaN HEMT devices: Role of reverse-bias and hot electron stress," Microelectron. Eng. **109**, 257–261 (2013).
[11]M. Meneghini, O. Hilt, C. Fleury, R. Silvestri, M. Capriotti, G. Strasser, D. Pogany, E. Bahat-Treidel, F. Brunner, A. Knauer, J. Würfl, I. Rossetto, E. Zanoni, G. Meneghesso, and S. Dalcanale, "Normally-off GaN-HEMTs with p-type gate: Off-state degradation, forward gate stress and ESD failure," Microelectron. Reliab. **58**, 177–184 (2016).
[12]M. Meneghini, G. Cibin, M. Bertin, G. A. M. Hurkx, P. Ivo, J. Sonsky, J. A. Croon, G. Meneghesso, and E. Zanoni, "OFF-state degradation of AlGaN/GaN power HEMTs: Experimental demonstration of time-dependent drain-source breakdown," IEEE Trans. Electron Devices **61**(6), 1987–1992 (2014).
[13]P. Makaram, J. Joh, J. A. Del Alamo, T. Palacios, and C. V. Thompson, "Evolution of structural defects associated with electrical degradation in AlGaN/GaN high electron mobility transistors," Appl. Phys. Lett. **96**(23), 233509 (2010).
[14]A. Sozza, C. Dua, E. Morvan, M. A. Diforte-Poisson, S. Delage, F. Rampazzo, A. Tazzoli, F. Danesin, G. Meneghesso, E. Zanoni, A. Curutchet, N. Malbert, N. Labat, B. Grimbert, and J.-C. D. Jaeger, "Evidence of traps creation in GaN/AlGaN/GaN HEMTs after a 3000 hour on-state and off-state hot-electron stress," in *IEEE International Electron Devices Meeting-Technical Digest (IEDM)* (IEEE, 2005).
[15]M. Ťapajna, R. J. T. Simms, Y. Pei, U. K. Mishra, and M. Kuball, "Integrated optical and electrical analysis: Identifying location and properties of traps in AlGaN/GaN HEMTs during electrical stress," IEEE Electron Device Lett. **31**(7), 662–664 (2010).
[16]Y. Wu, C. Y. Chen, and J. A. del Alamo, "Electrical and structural degradation of GaN high electron mobility transistors under high-power and high-temperature Direct Current stress," J. Appl. Phys. **117**(2), 025707 (2015).
[17]X. Niu, X. Ma, B. Hou, L. Yang, Y. S. Lin, Q. Zhu, F. M. Ciou, K. H. Chen, Y. Chen, J. Du, M. Wu, M. Zhang, C. Wang, T. C. Chang, and Y. Hao, "Electrical degradation of *in situ* SiN/AlGaN/GaN MIS-HEMTs caused by dehydrogenation and trap effect under hot carrier stress," IEEE Trans. Electron Devices **68**(9), 4283–4288 (2021).
[18]D. Bisi, M. Meneghini, M. Van Hove, D. Marcon, S. Stoffels, T.-L. Wu, S. Decoutere, G. Meneghesso, and E. Zanoni, "Trapping mechanisms in GaN-based MIS-HEMTs grown on silicon substrate," Phys. Status Solidi A **212**(5), 1122–1129 (2015).
[19]M. Meneghini, I. Rossetto, C. D. Santi, F. Rampazzo, A. Tajalli, A. Barbato, M. Ruzzarin, M. Borga, E. Canato, E. Zanoni, and G. Meneghesso, "Reliability and failure analysis in power GaN-HEMTs: An overview," in IEEE International Reliability Physics Symposium (IRPS), 2017.
[20]G. Meneghesso, G. Verzellesi, F. Danesin, F. Rampazzo, F. Zanon, A. Tazzoli, M. Meneghini, and E. Zanoni, "Reliability of GaN high-electron-mobility transistors: State of the art and perspectives," IEEE Trans. Device Mater. Reliab. **8**(2), 332–343 (2008).
[21]G. J. Syaranamual, W. A. Sasangka, R. I. Made, S. Arulkumaran, G. I. Ng, S. C. Foo, C. L. Gan, and C. V. Thompson, "Role of two-dimensional electron gas (2DEG) in AlGaN/GaN high electron mobility transistor (HEMT) ON-state degradation," Microelectron. Reliab. **64**, 589–593 (2016).
[22]D. K. Sahoo, R. K. Lal, K. Hyungtak, V. Tilak, and L. F. Eastman, "High-field effects in silicon nitride passivated GaN MODFETs," IEEE Trans. Electron Devices **50**(5), 1163–1170 (2003).
[23]G. Meneghesso, R. Pierobon, F. Rampazzo, G. Tamiazzo, E. Zanoni, J. Bernat, P. Kordos, A. F. Basile, A. Chini, and G. Verzellesi, "Hot-electron-stress degradation in unpassivated GaN/AlGaN/GaN HEMTs on SiC," in *Proceedings of the 43rd Annual IEEE International Reliability Physics Symposium* (IEEE, 2005), pp. 415–422.
[24]A. Zhang, Y. He, J. He, Y. Wei, G. Hu, C. Li, G. Ma, and R. Wang, "Stress Reliability Study of GaN HEMT Devices," in *IEEE International Conference on Advances in Electrical Engineering and Computer Applications (AEECA)* (IEEE, 2020), pp. 500–504.
[25]Z. H. Feng, Y. G. Zhou, S. J. Cai, and K. M. Lau, "Enhanced thermal stability of the two-dimensional electron gas in GaN/AlGaN/GaN heterostructures by Si3N4 surface-passivation-induced strain solidification," Appl. Phys. Lett. **85**(22), 5248–5250 (2004).
[26]M. Hou, S. R. Jain, H. So, T. A. Heuser, X. Xu, A. J. Suria, and D. G. Senesky, "Degradation of 2DEG transport properties in GaN-capped AlGaN/GaN heterostructures at 600 °C in oxidizing and inert environments," J. Appl. Phys. **122**(19), 195102 (2017).
[27]D. J. Chen, K. X. Zhang, Y. Q. Tao, X. S. Wu, J. Xu, R. Zhang, Y. D. Zheng, and B. Shen, "Temperature-dependent strain relaxation of the AlGaN barrier in AlGaN/GaN heterostructures with and without $Si_3N_4$ surface passivation," Appl. Phys. Lett. **88**(10), 102106 (2006).
[28]K. Shiojima and N. Shigekawa, "Thermal stability of electrical properties in AlGaN/GaN heterostructures," Jpn. J. Appl. Phys., Part 1 **43**(1R), 100 (2004).
[29]Z. Yanxu "Effects of rapid thermal annealing on ohmic contact of AlGaN/GaN HEMTs," J. Semicond. **35**(2), 026004 (2014).
[30]G. Greco, F. Iucolano, S. D. Franco, C. Bongiorno, A. Patti, and F. Roccaforte, "Effects of annealing treatments on the properties of Al/Ti/p-GaN interfaces for normally OFF p-GaN HEMTs," IEEE Trans. Electron Devices **63**(7), 2735–2741 (2016).
[31]M. A. J. Rasel, S. Stepanoff, A. Haque, D. E. Wolfe, F. Ren, and S. Pearton, "Non-thermal annealing of gamma irradiated GaN HEMTs with electron wind force," ECS J. Solid State Sci. Technol. **11**(7), 075002 (2022).
[32]N. S. Al-Mamun, M. A. J. Rasel, D. E. Wolfe, A. Haque, R. Schoell, K. Hattar, S. H. Ryu, and S. K. Kim, "Mitigating heavy ion irradiation-induced degradation in p-type SnO thin-film transistors at room temperature," Phys. Status Solidi A **220**, 2300392 (2023).
[33]Z. Islam, A. Kozhakhmetov, J. Robinson, and A. Haque, "Enhancement of WSe2 FET performance using low-temperature annealing," J. Electron. Mater. **49**(6), 3770–3779 (2020).
[34]N. S. Al-Mamun, D. E. Wolfe, A. Haque, J.-G. Yim, and S. K. Kim, "Room temperature annealing of $SnS_2$ films with electron impulse force," Scr. Mater. **224**, 115107 (2023).
[35]Z. Islam, H. Gao, and A. Haque, "Synergy of elastic strain energy and electron wind force on thin film grain growth at room temperature," Mater. Charact. **152**, 85–93 (2019).
[36]D. C. Pagan, M. A. J. Rasel, R. E. Lim, D. Sheyfer, W. Liu, and A. Haque, "Non-destructive depth-resolved characterization of residual strain fields in high electron mobility transistors using differential aperture x-ray microscopy," J. Appl. Phys. **132**(14), 144503 (2022).
[37]M. Leszczynski, T. Suski, H. Teisseyre, P. Perlin, I. Grzegory, J. Jun, S. Porowski, and T. D. Moustakas, "Thermal expansion of gallium nitride," J. Appl. Phys. **76**(8), 4909–4911 (1994).
[38]M. Leszczynski, H. Teisseyre, T. Suski, I. Grzegory, M. Bockowski, J. Jun, S. Porowski, K. Pakula, J. M. Baranowski, C. T. Foxon, and T. S. Cheng, "Lattice parameters of gallium nitride," Appl. Phys. Lett. **69**(1), 73–75 (1996).
[39]M. Leszczynski, T. Suski, P. Perlin, H. Teisseyre, I. Grzegory, M. Bockowski, J. Jun, S. Porowski, and J. Major, "Lattice constants, thermal expansion and compressibility of gallium nitride," J. Phys. D **28**(4A), A149 (1995).
[40]G. Meneghesso, F. Rampazzo, P. Kordos, G. Verzellesi, and E. Zanoni, "Current collapse and high-electric-field reliability of unpassivated GaN/AlGaN/GaN HEMTs," IEEE Trans. Electron Devices **53**(12), 2932–2941 (2006).
[41]J. Zhao, Z. Lin, T. D. Corrigan, Z. Wang, Z. You, and Z. Wang, "Electron mobility related to scattering caused by the strain variation of AlGaN barrier layer in strained AlGaN/GaN heterostructures," Appl. Phys. Lett. **91**(17), 173507 (2007).
[42]Y. J. Lv, X. B. Song, Y. G. Wang, Y. L. Fang, and Z. H. Feng, "Influence of surface passivation on AlN barrier stress and scattering mechanism in ultra-thin AlN/GaN heterostructure field-effect transistors," Nanoscale Res. Lett. **11**(1), 373 (2016).
[43]B.-J. Kim, Y.-H. Hwang, S. Ahn, W. Zhu, C. Dong, L. Lu, F. Ren, M. R. Holzworth, K. S. Jones, S. J. Pearton, D. J. Smith, J. Kim, and M.-L. Zhang, "Recovery in dc and rf performance of off-state step-stressed AlGaN/GaN high electron mobility transistors with thermal annealing," Appl. Phys. Lett. **106**(15), 153504 (2015).

[44]M. Kuball, M. Ťapajna, R. J. T. Simms, M. Faqir, and U. K. Mishra, "AlGaN/GaN HEMT device reliability and degradation evolution: Importance of diffusion processes," Microelectron. Reliab. **51**(2), 195–200 (2011).
[45]T. Roy, Y. S. Puzyrev, B. R. Tuttle, D. M. Fleetwood, R. D. Schrimpf, D. F. Brown, U. K. Mishra, and S. T. Pantelides, "Electrical-stress-induced degradation in AlGaN/GaN high electron mobility transistors grown under gallium-rich, nitrogen-rich, and ammonia-rich conditions," Appl. Phys. Lett. **96**(13), 133503 (2010).
[46]J. Chen, Y. S. Puzyrev, R. Jiang, E. X. Zhang, M. W. McCurdy, D. M. Fleetwood, R. D. Schrimpf, S. T. Pantelides, A. R. Arehart, S. A. Ringel, P. Saunier, and C. Lee, "Effects of applied bias and high field stress on the radiation response of GaN/AlGaN HEMTs," IEEE Trans. Nucl. Sci. **62**(6), 2423–2430 (2015).
[47]Y. S. Puzyrev, T. Roy, E. X. Zhang, D. M. Fleetwood, R. D. Schrimpf, and S. T. Pantelides, "Radiation-induced defect evolution and electrical degradation of AlGaN/GaN high-electron-mobility transistors," IEEE Trans. Nucl. Sci. **58**(6), 2918–2924 (2011).
[48]R. Jiang, X. Shen, J. Fang, P. Wang, E. X. Zhang, J. Chen, D. M. Fleetwood, R. D. Schrimpf, S. W. Kaun, E. C. H. Kyle, J. S. Speck, and S. T. Pantelides, "Multiple defects cause degradation after high field stress in AlGaN/GaN HEMTs," IEEE Trans. Device Mater. Reliab. **18**(3), 364–376 (2018).
[49]S. Dolabella, A. Borzì, A. Dommann, and A. Neels, "Lattice strain and defects analysis in nanostructured semiconductor materials and devices by high-resolution x-ray diffraction: Theoretical and practical aspects," Small Methods **6**(2), 2100932 (2022).
[50]N. S. Al-Mamun, M. Wetherington, D. E. Wolfe, A. Haque, F. Ren, and S. Pearton, "Local strain modification effects on global properties of AlGaN/GaN high electron mobility transistors," Microelectron. Eng. **262**, 111836 (2022).
[51]N. S. Al-Mamun, S. Stepanoff, A. Haque, D. E. Wolfe, F. Ren, and S. Pearton, "Localized strain relaxation effect on gamma irradiated AlGaN/GaN high electron mobility transistors," Appl. Phys. Lett. **121**(23), 233502 (2022).