Identification of an RF degradation mechanism in GaN based HEMTs triggered by midgap traps

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Abstract

Quantitative defect spectroscopy was performed on low gate leakage operational S-band GaN HEMTs before and after RF accelerated life testing (ALT) to investigate and quantify potential connections between the evolution of observed traps and RF output power loss in these HEMTs after stressing. Constant drain current deep level transient spectroscopy and deep level optical spectroscopy (CI_D-DLTS and CI_D-DLOS, respectively) were used to interrogate thermally-emitting traps (CI_D-DLTS) and deeper optically-stimulated traps (CI_D-DLOS) so that the entire bandgap can be probed systematically before and after ALT. Using drain-controlled CI_D-DLTS/DLOS, with which traps in the drain access region are resolved, it is found that an increase in the concentration of a broad range of deep states between E_C-1.6 to 3.0 eV, detected by CI_D-DLOS, causes a persistent increase in on-resistance of ~0.22 Ω-mm, which is a likely source for the 1.2 dB reduction in RF output power that was observed after stressing. In contrast, the combined effect of the upper bandgap states at E_C-0.57 and E_C-0.72 eV, observed by CI_D-DLTS, is responsible for only ~ 10% of the on-resistance increase. These results demonstrate the importance of discriminating between traps throughout the entire bandgap with regard to the relative roles of individual traps on degradation of GaN HEMTs after ALT.

Keywords: Gallium nitride, high electron mobility transistors (HEMTs), traps, degradation, reliability, deep level transient spectroscopy (DLTS), deep level optical spectroscopy (DLOS)

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1. Introduction

Electrically active defects acting as charge trapping centers in GaN HEMTs have been the subject of intense research for more than a decade [1]–[4]. Traps can significantly deteriorate the switching performance of devices and thereby limit their long-term reliability [1]–[4]. It is therefore important to be able to directly and quantitatively detect traps throughout the bandgap within operational GaN HEMTs as a function of their design and operational history. To that end, constant drain current deep level transient spectroscopy (CI_D -DLTS), based on trap detection via thermally-stimulated emission, and deep level optical spectroscopy (CI_D -DLOS), based on optically-stimulated emission to observe very deep traps, were developed for application to GaN HEMTs. [5]–[8]. Arehart *et al.* reported the initial application of these methods to RF stressed HEMTs, revealing the presence of a trap at $E_C-0.57$ eV in the drain access region that was directly linked to power loss in those devices. This deep level matched earlier reported observations of this level in GaN HEMTs [3]. Later investigation of this defect by Sasikumar *et al.* [9], [10] and Cardwell *et al.* [11] showed that its physical location is within the GaN buffer. While emphasis was placed on discussion of the properties and location of the $E_C-0.57$ eV trap, observed using CI_D -DLTS in the drain-controlled CI_D -DLTS mode, which senses traps in the drain access region, it is noteworthy that drain controlled CI_D -DLOS measurements performed on these same GaN HEMTs detected much deeper traps within the bandgap in the drain-access regions. However for those devices, no systematic correlation was observed between the evolution

of very deep trap states and the output power degradation seen [5]–[8], with the entire degradation being fully explained by the behavior and properties of the $E_C-0.57$ eV trap.

However, such observations might not be generalizable to all GaN HEMTs from all vendors as will be shown in this communication. There have been few reports in the literature directly linking much deeper traps, i.e. for $E_C-E_T > 1$ eV, to transistor performance and reliability [2], [4], [6]. This is undoubtedly due to the difficulty in probing very deep states in GaN by methods other than DLOS. This paper reports a systematic study on a series of low gate leakage S-band GaN HEMTs for which very deep states (with activation energies ranging between $E_C-1.6$ to 3.0 eV) in fact do have a direct impact on transistor on-resistance that subsequently causes RF performance degradation. While the much-discussed $E_C-0.57$ eV trap, along with other thermally detected (“shallower”) traps in the upper part of the bandgap were observed, it is found that they are not generally influenced by RF electrical stressing in this particular series of GaN HEMTs, which display very low gate leakage currents compared to prior studies of a similar nature [5], [9]–[11].

2. Sample description and RF stressing experiment

A series of four S-band RF AlGaIn/GaN HEMTs were supplied from a commercial vendor. A two dimensional electron gas (2DEG) density n_s of $\sim 1 \times 10^{13} \text{ cm}^{-2}$ and a mobility value of $\sim 1900 \text{ cm}^2/\text{Vs}$ were measured using Hall-effect. These HEMTs had SiN_x passivation in the access regions with a 0.4 mm of gate periphery. All four devices had nominally identical electrical characteristics before application of any stressing. The transistors had a maximum drain current of 0.6 A/mm before stressing at

$V_{GS} = 0$ V and a threshold voltage of -3.2 V measured at $V_{DS} = 10$ V. Each of these HEMTs also had very low gate leakage ($\sim 10^{-8}$ A/mm), measured at $V_{GS} < V_T$ and $V_{DS} = 10$ V. The results from one device will be presented as representative of the lot since all four HEMTs were identical to each other before and after the RF stressing experiments. The HEMTs were subjected to accelerated life testing at 3.5 GHz frequency using class AB switching scheme with a DC operating point of $V_{DS} = 48$ V, and $I_{DS} = 0.21$ A/mm, RF input power of 21 dBm while maintaining a baseplate temperature of 150 °C for 250 hours. The effect of the RF stressing on the different RF metrics of the HEMTs are shown in Figs. 1 and 2.

Even though the RF life testing was performed at a higher baseplate temperature of 150 °C, the sampling of these properties was performed at a baseplate temperature of 60 °C. To do so, the stressing experiment at high temperature was interrupted and the baseplate temperature was lowered to 60 °C in order to monitor the output power under more normal operational conditions. From Fig. 2 it is clear that a major portion of the degradation, an RF output power drop from 33.3 dBm to 32.1 dBm, occurs within the first 20 hours of the RF life testing. Between 20 and 100 hours, the HEMT output power recovers to around 32.2 dBm and settles there for the rest of the stressing duration of up to 250 hours bringing the overall RF output power reduction to about ~ 1.2 dB.

3. Experimental trap characterization methods

Drain-controlled CI_D -DLTS measurements were made on the HEMTs (sensitive to upper band-gap states in the drain access region) using a fill pulse of $V_{GS} = -3.9$ V and $V_{DS} = 10$ V for a duration of 100 ms. The drain-control aspect of the measurement

ensures sensitivity to the drain access region only. The V_{DS} transients were recorded immediately following the fill pulse to maintain a constant current of 0.175 A/mm at $V_{GS} = 0$ V in the triode regime at different temperatures (ranging from 77 to 430 K in 0.1 K steps). The constant drain current value was optimized to simultaneously reduce to negligible levels, self-heating effects occurring during the measurement and still give a measureable trap response. The V_{DS} transient at constant current I_{DS} is converted to a drain resistance transient using $\Delta R_D = \Delta V_{DS}/I_{DS}$. Box-car analysis of the ΔR_D thermal transients for a given time rate-window gives rise to negative peaks which are representative of electron traps. The trap concentration is extracted using the amplitude of measured ΔR_D CI_D -DLTS peaks in conjunction with the Hall measured n_s and μ_n values using relations that have been previously published [5]–[8]. Arrhenius analysis of the CI_D -DLTS peaks for different rate windows yields the thermal trap activation energy (referred to the conduction band edge) and apparent thermal capture cross-section of the trap. The drain-controlled CI_D -DLTS is only sensitive to traps (in the drain access region of the transistor) with $E_C - E_T < 1$ eV (because deeper traps have very slow thermal emission rates). Such upper band gap drain access region states are responsible for time transient effects that are recoverable in relatively short times (< few hundred seconds) at room temperature.

In order to investigate even deeper drain access region traps that could potentially produce a more persistent or apparently permanent effect on the on-resistance, optical methods, such as lighted DC IV and drain-controlled CI_D -DLOS measurements were applied. In the lighted IV technique the output drain current versus drain voltage

characteristics at $V_{GS} = 0$ V are first recorded in the dark and the on-resistance of the transistor is extracted from the triode region. This steady state on-resistance reflects the state of the 2DEG with all deep electron trap states in the band-gap filled with electrons. Next the sample is illuminated with sub-bandgap monochromatic light to selectively empty any filled deep levels energy ($E_C - E_T$) less than the photon energy $h\nu$ (i.e. from the conduction band edge to $E_C - h\nu$). If the energy of the monochromatic sub-bandgap light exceeds the optical activation energy of a deep state, then optically assisted electron emission from a filled state occurs, thereby effectively reducing the previously trapped negative charge. The reduction of negative charge in the system recovers the 2DEG density, n_s , in the access regions. This increase in 2DEG density increases the parasitic channel conductivity and thereby reduces the transistor on-resistance. This technique can be used as a quick non-destructive and non-invasive survey tool of optically active traps affecting the properties of a real operational device.

A higher-resolution, more thorough and quantitative identification of these very deep levels is achieved through application of the constant drain-controlled CI_D -DLOS methods [5], [6]. The drain-controlled CI_D -DLOS measurement was performed at a constant drain current $I_{DS} = 0.175$ A/mm by dynamically controlling the drain voltage V_{DS} measured with $V_{GS} = 0$ V applied on the HEMT as a function of incident sub-bandgap monochromatic light with photon energies tunable (in 0.02 eV increments) in the range of 1.2 to 4.5 eV. That is, the CI_D -DLOS measurement monitors the steady state drain resistance changes in the HEMT as a function of incident photon energy before and after the RF life-testing. The energy values of the negative onsets in the photoresponse

represent the optical activation energies of deep traps detected in the GaN HEMT drain access region. The magnitude of the step height associated with each negative onset of ΔR_D may be used to extract the concentration of the particular deep trap in question. More details about the CI_D -DLOS methods have been published elsewhere, and this includes the relations to extract concentration of traps using measured ΔR_D onset amplitudes [5], [6].

4. Results and discussion

The DC transfer IV characteristic of the HEMTs in this work before and after RF stressing is shown in Fig. 3. No measurable V_T shift was observed in the transfer IV characteristics measured at room temperature with $V_{DS} = 10$ V and $V_{DS}=0.1$ V. This observation suggests that no change in 2DEG density occurred under the gate which in turn suggests that minimal trapping effects were activated under the gate as a function of the RF stressing. Furthermore, although a drain induced barrier lowering (DIBL) effect of ~ 22.6 mV/V was detected in the V_T of both the stressed and unstressed GaN HEMTs, because its effect is common to both the devices, the DIBL effect does not explain the observed output power degradation (seen in Figs. 1 and 2). The DC output IV characteristics (see Fig. 4) collected in the transistors for ($V_{GS} = 0$ V) before and after the RF stress revealed an increase in on-resistance as is clear from the in the decrease in slope of the IV characteristics extracted from the triode regime of the transistor's operation. The increase in on-resistance by ~ 0.2 Ω -mm in these HEMTs after the RF stressing suggests that access region trap formation/activation is likely occurring as a function of the accelerated life test. Because the RF stressing occurred in the presence of

a high V_{DS} and high fields at the gate-drain edge, it is likely that the persistent knee-walkout in these HEMTs is due to *drain access region* trap formation/activation reducing the 2DEG density in the parasitic drain access region. The subsequent increase in the transistor on-resistance and related knee-walkout is the most probable cause for the observed output power reduction in these HEMTs.

To first investigate whether upper bandgap drain-access region traps were responsible for the observed on-resistance increases, drain-controlled CI_D -DLTS was performed [5]–[8]. As seen in Fig. 5, before application of any RF stressing, no sign of the E_C –0.57 eV trap was detected in these HEMTs. The absence of the E_C –0.57 eV trap signature could be related to the fact that these HEMTs have very low off-state gate-leakage ($\sim 10^{-8}$ A/mm), which is at least two orders of magnitude lower than the gate leakage in the GaN HEMTs from all previous reports where the E_C –0.57 eV trap was widely detected [5], [7], [9]–[11]. This connection of the E_C –0.57 eV trap presence with gate-leakage is further reinforced by the observation of the E_C –0.57 eV signature as a shoulder after RF stressing when the gate leakage current also showed a measurable ($\sim 400\times$) increase. From the peak height, the sheet concentration of E_C –0.57 eV trap detected after stressing was in the order of $1.5 \times 10^{11} \text{ cm}^{-2}$. These observations suggest that there is a clear relationship between the reverse gate leakage and the E_C –0.57 eV trap in agreement with recent reports in literature that propose the high off-state gate leakage may be a filling mechanism (and necessary condition) that enables detection of the E_C –0.57 eV trap [12]. Apart from the E_C –0.57 eV trap, the GaN devices also showed presence of an E_C –0.72 eV electron trap at concentrations of $8.8 \times 10^{12} \text{ cm}^{-2}$ before

stressing that slightly increased to $9.2 \times 10^{12} \text{ cm}^{-2}$, which causes a small increase of drain resistance from 0.10 to 0.13 $\Omega\text{-mm}$. The Arrhenius data of both the $E_C-0.57$ and $E_C-0.72$ eV trap show excellent agreement (see Fig. 6) with that collected from bulk GaN materials studies in the past [13]. This overlap suggests that both these levels are located within the GaN buffer. The slight increases in concentration of the $E_C-0.57$ eV and $E_C-0.72$ eV traps accounts for <10% of the total on-resistance increase of $\sim 0.2 \text{ }\Omega\text{-mm}$ observed in the output IV characteristics in Fig. 4, indicating their minor role with respect to power reduction in the HEMTs after ALT.

As expected, the $E_C-0.57$ and $E_C-0.72$ eV trap are not responsible for the static knee walkout and therefore deeper states were probed using optical methods including lighted output IV and drain-controlled CI_D -DLOS methods. The DC IV characteristics of the GaN HEMTs before and after the RF stressing are recorded in the dark and with 1.2 eV and 3.0 eV monochromatic light incident on the sample. The results of these measurements are summarized in Fig. 7. In the dark, the stressed HEMT showed a larger on-resistance in comparison to the RF stressed HEMT. With 1.2 eV light incident on the HEMT, there is negligible recovery of the on-resistance in either the unstressed and RF stressed HEMTs. This result shows that the states between $E_C-0.72$ eV and $E_C-1.2$ eV have no influence over the steady state on-resistance of the HEMT. In contrast, application of 3.0 eV energy light on the HEMT almost equalizes the on-resistance of the HEMT before and after the RF stressing by emptying all the trapped electrons within 3.0 eV of the conduction band edge suggesting that the most relevant electron traps must exist between $E_C-1.2$ eV and $E_C-3.0$ eV. The change in on-resistance in the unstressed

HEMT is due only to emission of electrons from pre-existing traps. In the stressed HEMT, the change is due to emission of electrons from both the pre-existing and the stressed-induced traps. While the detrapping of these optically excited deep states is temporary, the formation/activation of additional stress-induced levels in the RF stressed HEMT is permanent.

Having identified the range of trap energies responsible for the larger on-resistance/knee walkout, the higher resolution CI_D -DLOS measurements were performed, giving a steady state photoresponse of the transistor as shown in Fig. 8. The largest increase in the ΔR_D signal (by $\sim 0.22 \text{ } \Omega\text{-mm}$) was observed within a broad energy range of 1.6 and 3.0 eV, which closely matches the $\sim 0.2 \text{ } \Omega\text{-mm}$ increase in on-resistance noted in the HEMT output IV curves in Fig. 4 and provides a direct correlation between the mid-gap trap formation and the on-resistance increase observed after the RF stressing. The broad nature of the CI_D -DLOS onset in this E_C -1.6 to 3.0 eV energy range suggests a distribution of mid-gap and lower band-gap traps states after the RF stressing. The change in on-resistance produced by the CI_D -DLOS detected traps in the E_C -1.6 to 3.0 eV energy range is at least 9 times larger than that which was produced by the upper bandgap states detected using the CI_D -DLTS. The corresponding increase in concentration of traps after the RF stressing within this energy range is $\sim 1 \times 10^{12} \text{ cm}^{-2}$. These results imply that the deep traps are the likely cause of the observed RF degradation through the increase of persistent on-resistance in these low leakage GaN HEMTs.

Finally, and in order to provide completeness with respect to the role(s) of all detected traps, other even deeper discrete states with sharp negative onsets at $E_C-3.25$ eV and $E_C-3.8$ eV (i.e. near the valence band edge) were observed and analyzed before and after stressing by CI_D -DLOS measurements made on the GaN HEMTs. However, the magnitude of the ΔR_D , and therefore trap concentrations, associated with these levels ($\sim 0.25 \times 10^{12} \text{ cm}^{-2}$) remained unaffected after the stressing. The $E_C-3.25$ has been previously reported to be a GaN buffer trap that correlates with the presence of residual carbon manifesting as C_N substitutional defects [14]–[16]. The $E_C-3.8$ eV, simply by virtue of its activation energy being larger than the GaN bandgap, must be an AlGaIn trap, and has been reported previously [17].

5. Conclusions

A combination of CI_D -DLOS and CI_D -DLTS was applied to industry-supplied S-band GaN HEMTs before and after ALT has revealed that the increase in static on-resistance/knee walkout due to ALT is due to a distribution of deep bandgap states with energies between $E_C-1.6$ and $E_C-3.0$ eV. Unlike previous reports, it was shown in these devices that the $E_C-0.57$ eV level appears relatively benign possibly as a result of the comparatively low gate leakage currents in these devices. The formation/activation of bandgap states in the range of $E_C - 1.6$ eV to 3 eV was directly linked to the increase in on-resistance of the GaN HEMTs after ALT which then leads to the observed output power degradation by ~ 1.2 dB suggesting a direct link between these deep levels and RF performance reduction.

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References

- [1] R. Vetry, N. Zhang, S. Keller, and U. Mishra, "The impact of surface states on the DC and RF characteristics of AlGaIn/GaN HFETs," *IEEE Trans. Electron Dev.*, vol. 48, 2001.
- [2] P. Klein, J. Mittereder, S. Binari, J. Roussos, D. Katzer, and, D. Storm, "Photoionization spectroscopy of traps in AlGaIn/GaN high electron mobility transistors grown by molecular beam epitaxy," *Electronics Lett.*, vol. 39, pp. 1354–5, 2003.
- [3] J. Joh, and J. del Alamo, "A current-transient methodology for trap analysis for GaN high electron mobility transistors," *IEEE Trans. Electron Devices*, vol. 58, pp. 132–140, 2011.
- [4] A. Armstrong, A. Allerman, A. Baca, C. Sanchez, "Sensitivity of on-resistance and threshold voltage to buffer-related deep level defects in AlGaIn/GaN high electron mobility transistors," *Semicond. Sci. Technol.*, vol. 28, pp. 0740201–6, 2013.
- [5] A. Arehart, A. Sasikumar, G. Via, B. Wittingham, B. Poling, E. Heller, and S. A. Ringel, "Spatially-discriminating trap characterization methods for HEMTs and their application to RF-stressed AlGaIn/GaN HEMTs," in *IEDM Tech. Dig.*, 2010, pp. 20.1.1-4.
- [6] A. Arehart, A. Malonis, C. Poblenz, Y. Pei, J. Speck, U. Mishra, and S. Ringel, "Next generation defect characterization in nitride HEMTs," *Phys. Stat. Solidi C*, vol. 8, pp. 2242–4, 2011.
- [7] A. Arehart, A. Sasikumar, S. Rajan, G. Via, B. Poling, B. Wittingham, E. Heller, D. Brown, Y. Pei, F. Recht, U. K. Mishra, and S. A. Ringel, "Direct observation of 0.57 eV trap-related RF output power reduction in AlGaIn/GaN high electron mobility transistors," *Sol. State Electron.*, vol. 80, pp. 19–22, 2013.
- [8] A. Sasikumar, A. Arehart, S. Kaun, J. Chen, E. Zhang, D. Fleetwood, R. Schrimpf, J. S. Speck, and S. A. Ringel, "Defects in GaN based transistors," in *Proc. of SPIE*, 8986, 2014, pp. 89861C1–9.
- [9] A. Sasikumar, A. Arehart, S. Martin-Horcajo, M. Romero, Y. Pei, D. Brown, F. Recht, M. di Forte-Poisson, F. Calle, M. Tadjer, S. Keller, S. DenBaars, U. Mishra, and S. Ringel, "Direct comparison of traps in InAlN/GaN and AlGaIn/GaN high electron mobility transistors using constant current deep level transient spectroscopy," *Appl. Phys. Lett.*, vol. 103, pp. 0335091–4, 2013.

- [10] A. Sasikumar, D. Cardwell, A. Arehart, J. Lu, S. Kaun, S. Keller, U. Mishra, J. Speck, J. Pelz, and S. Ringel, "Toward a physical understanding of the reliability-limiting $E_C-0.57$ eV trap in GaN HEMTs," in *IEEE Intl. Reliab. Phys. Symp.*, 2.C.1.1–6, 2014.
- [11] D. Cardwell, A. Sasikumar, A. Arehart, S. Kaun, J. Lu, S. Keller, J. Speck, U. Mishra, S. Ringel, and J. Pelz, "Spatially-resolved spectroscopic measurements of $E_C-0.57$ eV traps in AlGaIn/GaN high electron mobility transistors," *Appl. Phys. Lett.*, vol. 102, pp. 1935091–4, 2013.
- [12] M. Meneghini, I. Rossetto, D. Bisi, A. Stocco, A. Chini, A. Pantellini, C. Lanzieri, A. Nanni, G. Meneghesso, and E. Zanoni, "Buffer traps in Fe-doped AlGaIn/GaN HEMTs: Investigation of the physical properties based on pulsed and transient measurements," *IEEE Trans. Electron Devices*, vol. 61, pp. 4070–4077, 2014.
- [13] Z. Zhang, A. Arehart, E. Cinkilic, J. Chen, E. Zhang, D. Fleetwood, R. Schrimpf, B. McSkimming, J. Speck, and S. Ringel, "Impact of proton irradiation on deep level states in n-GaN," *Appl. Phys. Lett.*, vol. 103, pp. 0421021–5, 2013.
- [14] A. Hierro, A. Arehart, B. Heying, M. Mansen, U. Mishra, S. DenBaars, J. Speck, and S. Ringel, "Impact of Ga/N flux ration on trap states in n-GaN grown by plasma assisted molecular-beam epitaxy," *Appl. Phys. Lett.*, vol. 80, pp. 805–7, 2002.
- [15] A. Armstrong, C. Poblenz, D. Green, U. Mishra, J. Speck, and S. Ringel, "Impact of substrate temperature on the incorporation of carbon-related defects and mechanism for semi-insulating behavior in GaN grown by molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 88, pp. 0821141–3, 2006.
- [16] A. Armstrong, A. Arehart, B. Moran, S. DenBaars, U. Mishra, J. Speck, and S. Ringel, "Impact of carbon on trap states in n-type GaN grown by metal organic chemical vapor deposition," vol. 84, pp. 374–376, 2004.
- [17] A. Armstrong, A. Chakraborty, J. Speck, S. DenBaars, U. Mishra, and S. Ringel, "Quantitative observation and discrimination of AlGaIn- and GaN-related deep levels in AlGaIn/GaN heterostructures using capacitance deep level optical spectroscopy," *Appl. Phys. Lett.*, vol. 89, pp. 2621161–3, 2006.

Fig. 1. RF output power, gain and, power added efficiency before and after the RF accelerated life testing.

Fig. 2. Degradation of RF output power measured at baseplate temperature of 60 °C by interrupting the RF life testing (occurring at higher temperature of 150 °C). A reduction in output power by ~1.2 dB is observed as a function of the stressing experiment.

Fig. 3. Transfer IV characteristics of the GaN HEMTs measured at $V_{DS} = 10\text{ V}$ and $V_{DS}=0.1\text{ V}$ at room temperature. The threshold voltage of the HEMT remained mostly unaffected as a function of the RF stressing.

Fig. 4. A permanent increase in on-resistance (by $\sim 0.2\ \Omega\text{-mm}$) was observed from the static (or DC) IV characteristics of the GaN HEMT after the RF stressing. This knee-walkout is the likely mechanism behind the output power degradation post-stressing.

Fig. 5. Drain-controlled CLD-DLTS spectra of unstressed and RF stressed HEMTs detecting drain-access region electron traps. Before stressing only a single electron trap at $E_C - 0.72$ eV was detected. No sign of the ubiquitous $E_C - 0.57$ eV was detected pre-stressing. After stressing, slight formation of the $E_C - 0.57$ eV trap (by $\sim 1.5 \times 10^{11} \text{ cm}^{-2}$) was accompanied with an increase in $E_C - 0.72$ eV trap concentration (by $\sim 4 \times 10^{11} \text{ cm}^{-2}$).

Fig. 6. Arrhenius data extracted for the $E_C - 0.57$ and $E_C - 0.72$ eV traps for the GaN HEMT are compared against that collected for bulk GaN traps. Overlap of data strongly suggests that both traps occur in the GaN buffer.

Fig. 7. On-resistance data collected from DC output IV of the GaN HEMT before and after stress in the dark, with 1.2 eV, and with 3 eV monochromatic light shining on the GaN HEMT. After stress (and in the dark) the devices show higher R_{ON} indicating more negative charge in the access region after stress that reduces n_s thereby increasing resistance. There is no difference between dark and 1.2 eV illumination cases indicating that traps levels within 1.2 eV of the conduction band edge are not responsible for the increased R_{ON} . Lastly with 3.0 eV light shining there is a large reduction in R_{ON} indicating that deep states within the 1.2 to 3.0 eV range that were originally filled have now emitted electrons to become less negatively charged. This emission resulting in recovery of n_s and decrease of the on-resistance. The pre- and post-stress devices have nearly identical R_{ON} indicating that the deep states in the 1.2 to 3.0 eV range are likely responsible for the differences in on-resistance in pre- and post-stress cases in the dark.

Fig. 8. Drain-controlled CI_D-DLOS spectra of the low leakage GaN HEMTs measured before and after RF life testing. Deep traps with energies in the energy range of ~1.6 to 3.0 eV show the most increase and are directly responsible for the static on-resistance increase which likely contributes to the RF output power degradation.