Quantitative spectroscopy of reliability limiting traps in operational gallium nitride based transistors using thermal and optical methods

Dissertation

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Abstract

Gallium nitride (GaN) based high electron mobility transistors (HEMTs) have shown a lot of promise in high voltage, high power, and high radiation applications. However the full realization of the III-nitride potential and large scale adoption of this technology has been hindered by the existence of electrically active defects that manifest as deep levels in the energy bandgap. These deep levels can potentially act as charge trapping centers limiting device performance and long term reliability. It is therefore imperative to monitor these traps in operational GaN HEMTs as close as possible to their real world operational conditions. With that goal in mind, in this dissertation, a suite of advanced thermal and optical based trap spectroscopy methods and models collectively known as constant drain current deep level (thermal) transient spectroscopy and deep level optical spectroscopy (CID-DLTS/DLOS) were developed and expanded upon to directly probe and track traps in three terminal operational GaN HEMTs. These techniques have allowed an unprecedented ability to quantitatively track trap levels throughout the wide bandgap of operational GaN devices and depending on their mode of switching (gate-controlled versus drain-controlled) are able to distinguish between under gate and access region defects as a function of device design and/or operational history. The devices studied here were subjected to a range of different stressors and very
different trap induced degradation mechanisms were identified that further confirms the need for such high resolution defect spectroscopic studies in GaN HEMTs. Specifically the GaN HEMTs studied here were subjected to three very different kinds of stressors, i) high frequency moderate drain voltage (<50 V) accelerated lifetime stressor, ii) very high off-state drain voltage (up to 600 V) stressors applied to GaN-on-Si MISHEMTs optimized for power switching applications, and iii) high energy particle irradiation (in this case 1.8 MeV protons) stressor applied to high frequency GaN HEMTs targeted for space applications. In the case of the RF life testing, the GaN HEMTs over an array of different suppliers (mostly commercial), an $E_C-0.57$ eV trap was identified as occurring almost ubiquitously and determined to be causing knee-walkout, drain-lag and linked directly to RF output power loss through its trapping/detrapping activity in the drain access region. This level was unambiguously located in the GaN buffer using a combination of ClD-DLTS/DLOS, and supporting nano-scale DLTS/DLOS approaches. It was observed that the detection of this buffer trap was observed to be highly dependent on the reverse gate leakage of the GaN HEMTs and an empirical leakage based filling model was proposed to describe the electron capture process in HEMT with leakage ($>10^{-7}$ A/mm). In contrast, for GaN HEMTs with very low reverse gate leakage ($<10^{-7}$ A/mm), a broad distribution of mid gap states between ($E_C-1.6$ to 2.5 eV) was found to be directly responsible for the RF output power loss through a persistent increase in on-resistance. The same ClD-DLTS/DLOS methods were adapted and expanded further to ensure applicability to high voltage GaN-on-Si power MISHEMTs up to very high drain voltages (up to 600V). On applying these advanced methods on commercial power
switching GaN MISHEMTs, a deep trap at $E_c-2$ eV was directly found responsible for very large current collapse effects after high voltage switching GaN-on-Si power HEMTs. This trap too was unambiguously located in the GaN buffer using a consensus of experimental results from constant capacitance DLOS and nanoscale DLOS on simple two terminal Schottky gate structures and past reports of a similar trap in carbon doped semi-insulating GaN. Lastly, proton irradiation effects on traps in GaN HEMTs targeted for space applications were studied and two major threshold instability mechanisms were identified. For proton fluences of up to $10^{14}$ cm$^{-2}$ a large persistent $V_T$ shift (~0.59 V) and a smaller switching dependent $V_T$ dispersion (~100-200 mV) were attributed to traps. Using Atlas Silvaco based simulations, the large and persistent $V_T$ shift was linked to very deep traps at $E_c-1.3$ and 3.28 eV both occurring in the GaN buffer. The $V_T$ dispersion increase was attributed to an $E_c-0.72$ eV trap concentration increase in the GaN buffer under the gate. Critical comparison of electrical stressor and irradiation stressors revealed that trap formation/activation in the electrically stressed devices occurred mostly in the drain access regions where the fields were highest. However in the GaN HEMTs exposed to particle irradiation, trap formation/activation occurred uniformly in the III-nitride material system due to uniform displacement damage occurring under the gate terminal and in the access regions. However, it was concluded that for the same damage i.e. for the same concentration of defects created, the impact of increased traps under the gate was far more severe on the device performance and reliability than the additional traps formed in the access regions. Through such a deeper understanding of trap assisted degradation mechanisms, more effective predictive
reliability models can be developed that will ultimately contribute to better growth/design strategies, performance, and reliability enhancement ultimately resulting in large-scale adoption of GaN electronics in RF and power applications.
Dedication

This document is dedicated to my wife.
Acknowledgments

I would like to offer my deepest appreciation and gratitude towards my advisor Prof. Steve Ringel for the uncompromising support and confidence he had in me right from the very day we met for the first time in a Starbucks at the Phoenix airport in 2009. All my achievements thus far in the academic program at OSU are largely owed to the timely advice, support (moral and financial), and creative freedom Steve has generously parted to me as well as his other students and researchers at EMDL. Equally important was the careful attention from Prof. Aaron Arehart who with his resourcefulness has steadfastly helped me and many others over the years with the nuts and bolts in the lab and beyond. Aaron is truly a pressure release valve in times of great stress and urgency engaging us all in soothing albeit insightful discussions ranging from semiconductors to politics (home and abroad) to international cuisine. I would like to thank Prof. Rajan for his excellent courses, engaging exams, and bright ideas. My respects go to Prof. Roblin for kindly taking the time and agreeing to be part of my candidacy and dissertation committee. The insightful comments from the whole committee is much appreciated and truly a character building experience. My thank you’s extend out to Prof. Jim Speck group and Prof. Umesh Mishra group, whose world-class GaN devices made this entire dissertation possible. I would like to acknowledge the robust collaboration with AFRL
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Chapter 1

Introduction

1.1 Motivation

The formidable requirements for RF power and high voltage high power switching applications exceed the practical and sometimes theoretical limits of traditional semiconductor based systems such as silicon (Si) and gallium arsenide (GaAs). Si and GaAs with bandgaps of 1.1 and 1.4 eV respectively cannot support large electric breakdown fields and therefore do not produce sufficient power during RF operation at high frequencies or they simply cannot be pushed to large blocking voltages for power switching applications. As is shown Fig. 1.1 when compared to the more established but dated vacuum tube technologies still used for certain high power radar applications, the solid state transistors clearly offers the more compact, faster, and versatile alternative [1].

Fig. 1.1 Relative dimensions of a vacuum tube (left) and a transistor (right) [2]
Table 1.1 Material properties of GaN versus other semiconductors (after Eastman et al. [1])

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.1</td>
<td>1.42</td>
<td>3.26</td>
<td>3.42</td>
</tr>
<tr>
<td>Electron mobility (cm²/Vs)</td>
<td>1500</td>
<td>8500</td>
<td>700</td>
<td>1500</td>
</tr>
<tr>
<td>Saturated electron velocity (×10⁷ cm/s)</td>
<td>1</td>
<td>1.3</td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td>Breakdown field (MV/cm)</td>
<td>0.3</td>
<td>0.4</td>
<td>3</td>
<td>3.3</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm°K)</td>
<td>1.5</td>
<td>0.5</td>
<td>4.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Fig. 1.2 Superior GaN device properties enabled by its material properties [3]
That said, the development of such a solid-state based technology for high speed switching at high voltages, high power, and sometimes at high temperature requires a semiconductor with high electron velocity and wide bandgap. This necessity is what fuels the great interest in wide bandgap semiconductors [1]. Among several options, the III-N materials system composed of GaN and its alloys, proves the most promising for applications in such particularly harsh environments.

Table 1.1 and Fig. 1.2 compares the GaN system to other semiconductor technologies. We can see why the GaN is system attractive for high frequency switching because of its high electron saturation velocity \((2.7 \times 10^7 \text{ cm/s})\) and high mobility of \(\sim 1500 \text{ cm}^2/\text{Vs}\) when fabricated as high electron mobility transistors (HEMTs). The wide bandgap of \(3.42 \text{ eV}\) (at room temperature) enables the high breakdown electric fields which in turn permits high voltage applications. The ability of this system to form a polarization induced quantum confined two dimensional electron gas (2DEG) with high sheet densities \((\sim 1-2 \times 10^{13} \text{ cm}^{-2})\) enables development of low noise devices capable of carrying high currents which when coupled with the high voltage capabilities ensures the high power carrying capacity of these devices. Furthermore its compatibility with 4H-SiC [and more recently with Si (111)] substrates, both materials with higher thermal conductivity, permits high temperature operation. These desirable properties have enabled GaN HEMTs to create its own space in defense related applications [1]. GaN HEMTs have also penetrated commercial market where a marriage between GaN to low-cost large-area Si substrates has triggered an electronics revolution of sorts especially in the high voltage switching applications (up to 600 V) [4].
Fig. 1.3 Measured threshold displacement energy versus inverse lattice constant of GaN compared to other semiconductors. The wideband gap semiconductors on the top right corner of this plot, namely SiC, GaN and diamond, are considered very radiation hard. (after I.-Nedelcescu et al., [5])

Fig. 1.4 Wide range of applications of GaN electronics exploiting full range of merits of GaN material system (from [6]). All these applications may be broadly categorized under three major categories of harsh environments circled (in red) that capture the major types of stressing/ageing stimulants to these devices under real world operation.
Yet another property of GaN that makes it desirable for extraterrestrial applications and other high particle radiation environments, is its radiation hardness [5]. Figure 1.3 shows how the GaN material system with its closely spaced lattice is rugged to incoming high energy particles such as protons, and electrons in high radiation environments. This radiation tolerance for GaN electronics coupled with its high power and high frequency capabilities make it an excellent choice for lightweight amplifiers that can be used for space exploration, missile guidance, and for reconnaissance purposes [5].

Figure 1.4 categorizes the various applications of GaN electronic devices. All these applications may be broadly classified under the following operational environments namely, high frequency, high voltage, high radiation, and high temperature [1].

Given that GaN HEMTs have applications targeted to such extreme operational conditions that push the material and the transistor to its limits, the question about device reliability becomes highly relevant. One of the greatest challenges preventing the large scale adoption of GaN HEMT technology is its limited reliability thanks to a variety or degradation mechanisms instigated by different stressors [7]–[10]. Solving the reliability gap in GaN electronics requires a deeper understanding of the physical mechanisms causing it. What’s more, a design or improvement that tends to bring about improved reliability also (in most cases) brings about an added reward of an enhancement of device performance which then advances the technology further.

To date, several mechanisms have been put forth to describe GaN HEMT degradation and reliability [7]–[13]. Many of these reports tentatively attribute the
observed degradation to existence, formation or activation of crystallographic defects in the GaN HEMT system. It is well known that GaN and its alloys have an inordinately high defect density despite years of progress in growth and processing [14], [15]. However the specific origin and nature of most of these defects remain uncertain and widely debated. Electrically active defects register in the forbidden energy band gap of these systems and act as charge trapping centers that affect the terminal current and voltage characteristics of the device [16]–[19]. These traps can be pre-existing, i.e. they were already present as a result of epitaxial growth of the component layers or formed during the fabrication process of the device. They can also be aggravated as a result of the harsh electrical operational history and/or high energy particle irradiation history [20]–[29]. There have been and still continue to be several efforts to characterize traps in operational GaN HEMTs in environments as close as possible to their harsh real world operational conditions [20]–[26]. Despite such grand campaigns, the problem of trap characterization and understanding their role in device reliability continues to be one of the great challenges of GaN electronics. To date, efforts to survey traps throughout the bandgap in operational GaN HEMTs as a function of real world stressors and correlating specific traps to observed degradation phenomenon have been sparse. It is precisely this lack of clarity about specific traps limiting the reliability of GaN HEMTs that acts as the primary catalyst motivating the work presented in this dissertation.

Assessing impact of deep traps in wide bandgap material based devices like GaN HEMTs is challenging partly because almost all trap spectroscopy techniques in existence
for GaN HEMTs are thermal based and therefore survey only part of the wide bandgap. Such techniques are ‘blind’ to traps occurring energetically farther than ~1 eV from the bandedges [30]–[32]. Detecting, isolating, and quantifying a specific defect in the wide bandgap of the composite layers of a HEMT with their multiple epitaxial layers, complex device geometry, and intricate lateral and electric field profiles in itself is a challenge. Correlating this specific trap, a material property, to an operational HEMT terminal characteristic such as $V_T$ instability or on-resistance, a device property, is the key to unlocking the puzzle that is GaN reliability. GaN HEMTs, with their ability to dissipate significant amounts of power also suffer from self-heating effects that could be misconstrued as charge trapping/detrapping [33]. Special care, therefore has to be taken to distinguish trapping from self-heating effects to develop an unadulterated understanding of GaN traps and their role in device degradation and reliability.

To overcome said challenges, an innovative suite of methods capable of studying deep states in operational HEMTs becomes imperative. Through such techniques, operational HEMTs can be studied as a function of a variety of real world electrical and/or radiation based stressors and the traps in them can be tracked and correlated to device performance loss. This collective understanding could inspire groundbreaking engineering solutions that could propel the widescale adoption GaN technology. An additional scientific impetus for such an effort would be that it creates opportunities to further add to the existing taxonomy of defects in the GaN and III-N alloy system thereby enhancing our fundamental understanding of crystal defects and trap levels in this fascinating material system.
Fig. 1.5 Bandgap vs. lattice constant for several binary compound semiconductors (after Jena et al. [34])

Fig. 1.6 Schematic illustration of GaN crystal in Ga-polar orientation (after Ambacher et al. [35]). Right panel illustrates how the polarization charges are neutralized in the bulk and are present only at the top and bottom surfaces of the GaN material grown along c-plane.
1.2 Background on the AlGaN/GaN HEMT

As shown in Fig. 1.5, the III-Nitride system occurs commonly in the wurtzite crystal structure. This configuration in nitrides lacks inversion symmetry along the c-axis which when combined with the partially ionic bond between the nitrogen and group III atoms gives rise to a residual dipole causing what is called a ‘spontaneous polarization’ along the c-axis [35]–[37]. Figure 1.6 shows GaN grown along the c-axis along Ga-polar orientation. A very large negative polarization sheet charge is present at the Ga-terminated face and an equal and opposite positive polarization charge is present at the N-terminated face. The spontaneous polarization, $P_{SP}$, for GaN is $-0.029$ C/m$^2$ whereas that of AlN is $-0.081$ C/m$^2$ because of the increased ionic nature of the bonds in the latter [35]–[37]. The spontaneous polarization for ternary Al$_x$Ga$_{1-x}$N compounds can be calculated approximately using [35]:

$$P_{SP}(\text{AlGaN}) = -0.090x - 0.034(1-x) + 0.019x(1-x) \text{ C/m}^2 \text{.................................(1.1)}$$

In addition to spontaneous polarization, a mechanical strain induced ‘piezoelectric’ polarization component exists. Due to the differences in the lattice constants of AlN and GaN (see Fig. 1.5), AlGaN layers grown pseudomorphically on relaxed GaN buffer layers are under biaxial tensile stress. The III-nitrides with the wurtzite crystal structure have large piezoelectric coefficients along the c-axis given by [35]:

$$P_{PE} = e_{33} \varepsilon_3 + e_{31}(\varepsilon_1 + \varepsilon_2) \text{ ........................................ (1.2)}$$

where $\varepsilon_1 = \varepsilon_2 = (a-a_0)/a_0$ is the in-place strain (assumed to be isotropic) and $\varepsilon_3 = (c-c_0)/c_0$ is the strain along the c-axis. Here $c_0$ and $a_0$ are the equilibrium values of the III-N
Fig. 1.7 Total polarization effect in a Ga-polar AlGaN/GaN HEMT (after Ambacher et al. [36]). The polarization effect results in the creation of a 2DEG with density $\sim 10^{13} \text{ cm}^{-2}$.

Fig. 1.8 Surface donor model for 2DEG formation in AlGaN/GaN HEMTs (after Ibbetson et al. [38]). The 2DEG is formed after a certain ‘critical’ thickness of the AlGaN barrier.
parameters in the absence of any strain. The piezoelectric constants, $e_{33}$ and $e_{31}$ are, respectively 0.73 and -0.49 C/m$^2$ for GaN, and 1.46 and -0.60 C/m$^2$ for AlN [3]. GaN HEMTs are often grown with a thick relaxed GaN buffer layer below a strained Al$_x$Ga$_{1-x}$N barrier layer. In such a system, the unstrained GaN buffer layer does not have a $P_{PE}$ component whereas the tensile strained Al$_x$Ga$_{1-x}$N has both a spontaneous and piezoelectric component as shown in Fig. 1.7. A net positive polarization charge results at the AlGaN/GaN interface given by $P_{SP}(\text{AlGaN}) + P_{PE}(\text{AlGaN}) - P_{SP}(\text{GaN})$.

It is this net polarization induced charge that enables formation of a high density two dimensional electron gas (2DEG) at that interface even in the absence of intentional doping. The currently accepted model for this 2DEG formation was put forth by Ibbetson et al. [38]. It was argued in [38] that the electric field inside the undoped AlGaN barrier is dependent on the sheet charges at the top and bottom faces. Since this field is constant, the potential drop between the two faces of the crystal increases linearly with an increase in the AlGaN barrier thickness. Beyond a critical thickness $d_{cr}$, as shown in Fig. 1.8, it becomes energetically more favorable for the system to create compensating charges of polarity opposite to the polarization charge at the AlGaN/GaN so as to lower the electric field in the AlGaN barrier. It is believed that free electrons from donor-type deep level surface states existing at the AlGaN surface provide the necessary compensating charge in form electrons that then form the 2DEG. In 1993 Khan and co-workers exploited this polarization induced 2DEG formed in the AlGaN/GaN system to fabricate the first AlGaN/GaN based HEMT [39], [40].
Fig. 1.9 Schematic cross-section of a Ga-polar AlGaN/GaN HEMT along with equilibrium energy band-diagram along a vertical cutline through the gated region. (from [41]). A voltage applied to the gate terminal modulates the polarization induced 2DEG charge under the gate, thereby controlling the drain to source current $I_{DS}$.

Figure 1.9 shows a schematic illustration of a conventional Ga-polar AlGaN/GaN HEMT. These devices are typically grown either using metal-organic chemical vapor deposition (MOCVD) or using molecular beam epitaxy (MBE). A 10-40 nm $\text{Al}_x\text{Ga}_{1-x}\text{N}$ film forms the barrier to the polarization induced 2DEG which exists in a triangular quantum well formed in the GaN channel layer [1].

Because GaN does not have a low-cost native substrate, these devices are typically grown on non-native SiC, Si, or sapphire substrates. For growth on such foreign substrates, a nucleation layers is typically first deposited to minimize crystal defects such as dislocations from extending into the top layers. This nucleation layer is then followed by a thick GaN buffer layer which is usually made semi-insulation using C or Fe dopants [1]. Semi-insulating buffers if designed correctly minimize parasitic conduction paths from the
source to drain contacts. The thickness and composition of the Al$_x$Ga$_{1-x}$N barrier film are chosen to produce the right amount of polarization using which a high-density 2DEG can be formed at the interface even in the absence of intentional donor doping. Typically Al composition $x$ ranges from 0.15 to 0.35 in AlGaN/GaN HEMTs. The source and drain contacts are annealed Ohmic contacts that electrically make contact with the 2DEG channel. The gate metal enables modulation of the 2DEG charge under it. The ungated regions between the source and the gate, and the gate and the drain are known as the source access region and drain access region, respectively. As shown in Fig. 1.9, the channel in the GaN HEMTs exist before application of any gate to source voltage. This means that these devices are ‘normally ON’ in nature [1]. Enhancement mode GaN based HEMTs also exist and are very promising and currently being developed for applications where normally OFF operation is preferred [42]. GaN HEMTs are also currently produced with additional features such as dielectrics under the gate, access region surface passivation [43], [44], and field plating [45], [46], to optimize their performance for target applications. State-of-the-art GaN HEMT devices have reported current densities in excess of 2 A/mm [47] and power densities as high as 40 W/mm (@ 4 GHz) [48]. Apart from Ga-polar GaN HEMTs, a wide variety of GaN HEMTs currently exist in N-polar orientation, that are highly-scaled HEMTs, that operate in enhancement mode, that are grown using MBE grown and in many more flavors in different phases of research and development. However, almost all of the GaN based HEMTs studied for purposes of reliability in this dissertation, are also the most commonly available type of commercial GaN HEMT, i.e. the depletion mode Ga-polar AlGaN/GaN devices grown using MOCVD.
1.3 Background on defects and their impact on GaN HEMTs

As mentioned earlier, despite the rapid maturity of GaN HEMT based electronics, the performance and reliability of these devices continues to be frustrated by ageing mechanisms of which several possible suspects are listed in Fig. 1.10. Of these many possible failure inducing mechanisms, the role of defects can clearly not be ignored. In this section, examples of defects limiting GaN HEMT terminal characteristics and performance will be presented. This background will set the stage for the purpose and objective of this dissertation work.

Fig. 1.10 Possible mechanisms limiting AlGaN/GaN HEMT reliability (from [48]).
The absence of an economically viable native GaN substrate forces researchers to fabricate GaN HEMT devices on non-native substrates such as SiC, Si, or sapphire. These materials are far from perfect matches to GaN, both in terms of lattice parameters and in terms of thermal properties. Attendant difficulties of this nature leads to a high density of extended and lattice defects as shown in Fig. 1.11. In addition to native point defects and extended defects like threading dislocations [14], [15], [49], impurity based defects can also incorporate in the bulk crystal during growth [16]–[19]. Aside from defects in the bulk material, GaN HEMTs have the added vulnerability of ungated surfaces where a large concentration of surface traps could potentially cause severe trapping effects and hamper device performance [22]–[24]. Moreover, the role of defects in dielectrics and interfaces also cannot be ignored in modern day GaN HEMT devices with high-k under-gate dielectrics and low-k access region dielectrics used as passivation layers [50], [51].

Fig. 1.11 Cross-sectional transmission electron micrograph (TEM) image of GaN grown using MOCVD on a sapphire substrate. (after Speck and Rosner [49]). Image shows a large density of threading dislocation defects extending from sapphire substrate to GaN surface.
These defects in the context of GaN HEMTs, can potentially degrade HEMT performance by acting as leakage (reverse gate leakage or buffer leakage) paths. The revere-bias gate leakage in HEMT devices has shown to be correlated to threading dislocations in AlGaN/GaN HEMTs grown using MBE [52]. Besides possibly acting as leakage paths, defects are believed to potentially manifest as deep levels in the forbidden energy bandgap and then act as charge trapping centers [16]–[19]. This relatively slow trapping and detrapping phenomenon affects the 2DEG density in the channel which then fails to respond to fast switching pulses resulting in poor switching characteristics. One of the major effects in AlGaN/GaN devices attributed to trapping in AlGaN/GaN HEMTs is the ‘current collapse’ which is a recoverable reduction in transistor drain current soon after application of high voltage between the drain and the gate terminal [53]–[56]. An early example of current collapse phenomenon in GaN HEMTs is shown in Fig. 1.12.

![Fig. 1.12. Earliest known report of current collapse in GaN HEMTs with (i) representing DC IV characteristics before application of V_{DS}=20 V and (ii) being the output DC IV characteristics after application of V_{DS}=20V (After Khan et al. [53])](image)
The GaN HEMT enters a high resistance mode despite removal of the high field conditions that caused it. Vetury et al. [57] proposed a surface trap based ‘virtual gate’ model. In this model, it is proposed that electrons from the gate metal tunnel into the access regions between the gate and the drain and get trapped in surface states resulting in a negative surface potential. This negative potential depletes the 2DEG channel beneath it much like a ‘virtual gate.’ While the potential on the real metal gate is controlled by the applied gate, bias, the potential on the second ‘virtual gate’ is controlled by the amount of trapped charge and how long it takes for the trapped charge to dissipate. The output drain current is now under the control of the virtual gate and the mechanisms that supplies charge to and removes charge from it. The discharging or detrapping process of this phenomenon is much slower (> milliseconds up to several thousand years depending on the temperature and how deep the traps are) than the response of 2DEG directly beneath the real gate. Thus while
these trapped charges may respond at low frequencies and DC, they are frozen in at higher frequencies. This means that the DC or static characteristics of the GaN HEMT may differ significantly from its RF or dynamic switching characteristics. This difference between DC and pulsed or RF characteristics of a GaN HEMT is known as RF to DC dispersion [58]. Careful HEMT design and fabrication techniques, the recovery time and degree of the drain current collapse has reduced dramatically over the years. That said, this phenomenon can still be observed even to this day but in significantly smaller degree in modern day GaN HEMTs. However, the current collapse phenomenon has been observed to increase after subjecting the GaN HEMTs to accelerated life testing conditions suggesting an increased formation/activation of traps responsible for the effect [54]. Therefore the current collapse phenomenon when amplified as a function of device aging can pose a serious threat to long term reliability.

The current collapse phenomenon can manifest as a gate-lag or a drain-lag where the drain current response of the transistor ‘lags’ the switching of the terminal voltages. If

![Normalized drain current response to gate pulse](image)

Fig. 1.14. Normalized drain current response to gate pulse $V_{GS}$ ($0 < t < 10 \mu s$), after off-state $V_{GS} = -10$ V pulse with bias of $V_{DS} = 10$ V applied continuously. Solid line shows a GaN HEMT with no gate-lag, whereas dotted line shows a GaN HEMT with significant gate lag. (after Mitrofanov and Manfra [59])
the drain current response to a gate voltage stimulus is delayed, the phenomenon is called ‘gate-lag.’[24], [59], [60] An example of a gate lag process is shown in Fig. 1.14. Binari et al. [24] tentatively attributed the gate lag phenomenon to electron trapping happening in surface traps located in the access regions. The reason for this assignment was an observation of decrease in the gate-lag phenomenon after surface passivation using silicon nitride. A complementary phenomenon, where the drain current lags a drain voltage stimulus is known as a drain lag [24]. According to Binari et al. [24], [60] the drain lag effects were mostly due to deep traps located the buffer regions of the AlGaN/GaN HEMT. The assignment of the trap origins to the GaN buffer was based on the fact that the same effects were also observed in GaN MESFET devices where there occurred no AlGaN barrier films although the role of surface traps was not completely ruled out.

In addition to degrading GaN HEMT IV performance, traps have been alleged in creation of physical defects like pits causing permanent in GaN HEMTs.

![Atomic force microscopy image showing structural damage induced by large reverse bias stress at the gate-drain edge.](image)

Fig. 1.15. Atomic force microscopy image showing structural damage induced by large reverse bias stress at the gate-drain edge [61]. The pit formation was accompanied with a sharp degradation in $I_G$, $I_{DS,max}$, and $I_{DS,lin}$. 
Figure 1.15 shows creation of pits on the AlGaN surface at the edge of the gate terminal closest to the drain [61]. Gao et al. [62] proposed a water assisted field induced electrochemical process that in combination with a trap assisted interband electron tunneling leads to the surface pitting and cracking at the gate-drain edge of GaN HEMTs under high fields. Apparently it is this trap assisted physical degradation mechanism that ruptures the AlGaN crystal and ultimately causes a permanent and drastic drop in drain current, increase in drain resistance, and substantial increase in gate leakage [62].

It is quite clear that the understanding the origin of traps in GaN HEMTs, their location, and physical mechanisms involved in trapping is important to achieve optimal device performance and enhanced reliability. In spite of considerable research effort that has been directed toward identification elimination of traps, there have not been quantitative correlations of specific trap levels in the III-Nitride bandgap to the observed and reliability and degradation phenomenon. This inconsistency in literature is partly related to the diversity of the trapping effects in the GaN devices and due to the varying material quality. However, without bridging the gap between materials and devices, the aggregate picture of traps and their impact on GaN HEMT reliability cannot be fully understood. It is essential therefore to develop a consistent, high resolution, quantitative and comprehensive kit of tools to interrogate GaN HEMTs in their operational environments to characterize traps in them and correlate their presence and properties to the operational history of those HEMTs under the influence of relevant stressors. It is towards this end that this dissertation work is geared as elaborated in the next section.
Fig. 1.16 Overview of this dissertation work
1.4 Objectives of this work

The purpose of the proposed research is to expand the base of methods and models, based on deep level transient spectroscopy (DLTS) and deep level optical spectroscopy (DLOS), such that these methods can be applied to real operational GaN HEMT devices as a function of real world stressors. As shown in Fig. 1.16, the constant current DLTS and DLOS (CI\textsubscript{D}-DLTS/DLOS) methods, recently developed for this purpose, were used, modified and expanded upon, to explore the quantitative nature of traps in a variety GaN based HEMTs and other advanced test structures both in control and electrically stressed and/or radiation degraded states. Such an approach allows quantitative tracking of key defects responsible for device performance degradation and other reliability problems as a function of the key stressors used in real world GaN applications. Everywhere possible, attempts were made to correlate the defects detected to the observed degradation. Using the correlations identified, degradation models were proposed that can be then used by researchers in the GaN and related areas to better understand and improve upon existing GaN technology. The CI\textsubscript{D}-DLTS/DLOS methods are applied to real transistors with complex geometries and field profiles, where unambiguous assignment of a specific defect to an individual component layer may not always be straightforward. In such cases, secondary tools such as pulsed IV, nano-scale DLTS/DLOS, numerical computer simulations using Silvaco’s Atlas software were adopted wherever necessary to explore possible the physical location of the critical defects and their other salient properties. The application of the novel and versatile CI\textsubscript{D}-DLTS/DLOS methods in conjunction with a wide range of supporting techniques in this
work has opened up unprecedented means towards linking specific defects to observed GaN HEMT degradation. Such efforts are especially valuable at this stage of GaN HEMT technology considering that it is on the cusp of wide scale adoption and the is the last major hurdle that needs to be overcome. is understanding and mitigating/solving the defect induced reliability problems. An additional motivation for such an effort, would be that it creates opportunities to nurture a basic understanding of defects in the III-Nitride system through the use of GaN HEMT device as a vehicle to study those defects in the composite materials. With a better understanding of the basic material properties and the defects in the GaN material system, and continuing improvement of its quality, we expect the superior characteristics of GaN to be fully realized through the devices fabricated from it.

1.5 Organization of this dissertation

Chapter 2 offers a survey of the major electrical and optical characterization techniques and models employed in this work, namely constant drain current CID-DLTS and DLOS. These techniques are based on the influence of deep level charge trapping and detrapping on GaN HEMT terminal characteristics such as on-resistance and threshold voltage, so the underlying fundamentals of these methods will be presented in addition to the biasing schemes of the individual techniques. In addition to CID-DLTS/DLOS methods, a brief discussion of supporting trap characterization techniques such as capacitance based DLTS/DLOS, pulsed IV, and nano-DLTS/DLOS will be provided. It is the appropriate application of the CID-DLTS/DLOS methods in combination with these supporting techniques that allow to track the traps, determine their location (wherever possible) and
obtain a deeper understanding of their properties in the operational GaN HEMTs before and after electrical or irradiation induced stressing.

It is useful to categorize the experimental results and discussion portion of this dissertation (Chapters 3 through 7) into three general sections. The first section comprising of Chapters 3 through 5 discuss the impact of RF electrical stressing on traps and reliability of GaN HEMTs. Specifically, Chapter 3 describe the effects of RF electrical stressing and how it results in the activation/formation of a specific Ec–0.57 eV trap. The observed degradation in those GaN HEMTs was then directly correlated to the increased concentration of this particular defect. Chapter 4 is a closer look at the same Ec–0.57 eV in an array of advanced GaN structures including HEMTs using ClD-DLTS and other advanced trap spectroscopy methods to isolate the location and properties of this critical and widely detected defect that was earlier thought to be occur in AlGaN barrier or surface. Through the evidence presented in Chapter 4 a consistent and unambiguous picture of its location is provided and revealed to be in the GaN buffer. A gate leakage based filling mechanism of this GaN buffer trap is also proposed where an empirical limit of 10^{-7} A/mm of reverse gate leakage was required to detect the Ec–0.57 eV trap.

Chapter 5 continues to assess the impact of RF stressing on GaN HEMTs with very low reverse gate leakage (< 10^{-7} A/mm) compared to the GaN HEMTs studied in Chapters 3 and 4. In these low leakage GaN HEMT devices much deeper traps were detected and directly correlated to the observed RF output power degradation.

The second section of results is composed of Chapter 6 that deals with GaN-on-Si power HEMTs subjected to high voltage stressors. A very deep trap at Ec–2 eV was
directly linked to a massive on-resistance degradation phenomenon in the three terminal GaN HEMT devices. Advanced trap spectroscopy on simpler two terminal Schottky diode structures revealed the physical location of this highly malignant Ec–2 eV trap to be in the GaN buffer.

The third and last section of the results comprises of Chapter 7 which consists of commercial GaN HEMTs subjected to high energy proton irradiation based stressors. It was observed that proton irradiation in GaN HEMTs primarily caused threshold voltage (V_T) instability which manifested in two ways. First, a permanent V_T shift (0.59 V) caused a 30% reduction in I_{DS,max} due to deep traps formed near mid-gap and valence band edge. Second, V_T dispersion (i.e., time- and voltage-dependent V_T shifts) increased by ~0.1 V as a result of an Ec–0.72 eV trap likely in the GaN buffer layer.

Finally Chapter 8 presents the conclusions derived from this work and offers suggestion for paths of future study.

1.6 References


Chapter 2

GaN HEMT trap characterization techniques

2.1 Introduction

The majority of previous trap studies in GaN [1]–[4] and related alloys [5], [6] was accomplished using capacitance based test structures. In capacitance deep level (thermal) transient spectroscopy (DLTS) [7] and deep level optical spectroscopy (DLOS) [8], [9] the effect of trap emission on the space charge in the depletion region of a diode (p-n junction or Schottky) is recorded as a capacitance transient during a measurement phase that follows immediately after a ‘fill pulse.’ The amplitude of the measured change in capacitance is proportional to the concentration of the trap responsible and the response of the transient time-constant as a function of temperature [7] or sub-bandgap light energy [8], [9] gives information about the trap energy level in the band gap. Capacitance based DLTS and DLOS methods have demonstrated the ability to detect the properties of traps in bulk materials with high degree of accuracy making these techniques an invaluable asset to fundamental material research, growth and process refinement, and quality control with an ultimate goal of device reliability improvement.
Despite all its virtues, the two terminal capacitance based measurements, cannot replicate all the complexities occurring in the modern day three-terminal GaN HEMTs. Granted the AlGaN/GaN heterostructures can be configured and measured in a two-terminal fashion [10], [11]. However such configurations cannot capture all the intricacies of the operation of a real three terminal GaN HEMT device with its complex vertical and lateral electric fields [12], [13]. Effects such as virtual gating [14], hot electrons [15], inverse piezoelectric effect [16], and other high lateral field induced effects are unique to the three-terminal configuration cannot be simulated in a two-terminal capacitance test structure [17]. Moreover, high frequency GaN HEMTs have far smaller gate peripheries (<~100x) compared to capacitance test structures making the measured capacitance very small (<10^{-12} F) and comparable to parasitic capacitances. To be able to correctly measure such small capacitances let alone be sensitive to very small changes in depletion capacitance exclusively due to trapping/detrapping of bandgap states is extremely difficult using standard capacitance meters with little guarantee of success.

Three terminal current-DLTS (I-DLTS) techniques were applied [18]–[20] to overcome such difficulties associated with the capacitance based two-terminal methods. These methods were originally developed for GaAs MESFETs [21]–[23] and later adopted to GaN HEMTs with little modification to the analysis and switching practices [18]–[20]. In addition to widely different material and device quality, the I-DLTS results suffered from high noise, conflicting trap energies, inconsistent switching schemes,. By far the greatest disadvantage of this early approach I-DLTS was that it was non-quantitative and therefore did not provide information of trap concentrations of the specific defects
identified. This qualitative aspect of I-DLTS had the undesirable consequence in that it was not possible for researchers to quantitatively compare defect concentrations across GaN HEMTs from different vendors, designs, or stressors. It is well known that much of the potency of the capacitance based DLTS/DLOS stems from its ability to clearly and quantitatively detect trap presence and concentration across a wide range of materials thereby allowing direct and detailed comparisons. Such a quantitative form of trap comparability is therefore naturally highly desired in the three terminal GaN HEMTs which I-DLTS fails to provide. Lastly, because the I-DLTS methods are all thermal based they allow spectroscopy of defects only within ~1 eV of the wide bandgap materials being investigated. To study even deeper traps sub band gap optical based spectroscopy methods had to be developed that simultaneously overcame said challenges of the two-terminal capacitance methods and the non-quantitative three terminal I-DLTS methods.

In 2009 Arehart et al. [24], [25] developed the first generation of the constant drain-current deep level (thermal) transient spectroscopy and deep level optical spectroscopy (CID-DLTS/DLOS) methods. The biggest distinction of CID-DLTS/DLOS methods compared to the I-DLTS methods was that a constant drain-current was maintained during the measurement condition where terminal voltages (either drain or gate) were recorded to extract trap specific information. The use of constant current greatly simplified extraction of trap information from HEMT triode and saturation regime. This was not possible in the simple I-DLTS methods of the past. What is more, the CID-DLTS/DLOS measurements also provide lateral spatial discrimination between traps.
Fig. 2.1 Energy band diagram of a semiconductor with deep levels (after Shockley et al. [37]). The four basic carrier emission and capture process are illustrated.

under the gate and in the access regions which again was not possible using traditional DLTS methods. This spatial sensitivity was achieved using two modes of switching namely (1) gate-controlled mode (sensitive to under gate traps) and (2) drain-controlled mode (sensitive to access-region traps). While a proof of concept of these newly developed techniques was achieved at the time [24], [25], optimization of the trap concentration extraction models and real world applicability of these methods across a range of real operational GaN HEMTs across a variety of stressors was achieved in this dissertation work [26]–[36]. Specifically in this Chapter, a series of necessary modifications/improvements to the originally developed models and switching schemes of CID-DLTS/DLOS are presented that eventually allowed correct, quantitative, consistent, and comprehensive extraction of trap concentrations in the operational GaN HEMT devices. [26]–[36] For a better appreciation of these trap spectroscopy methods, it
is useful to first recap the fundamentals of thermal and optical spectroscopies using the capacitance based DLTS [7] and DLOS [8], [9] as starting points.

2.2 Principles of thermal trap spectroscopy

When a crystal defect manifests as a state in the energy band diagram it may participate in one of the four competing process shown in Figure 2.1. Processes (a) and (b) in Fig. 2.1 represent electron capture and emission, respectively whereas process (c) and (d) represent hole capture and emission, respectively [37]. For purposes of simple illustration, we here use the case of a n-type GaN Schottky diode with almost no free holes in the system (in the absence above bandgap illumination), and therefore restrict our discussion to processes (a) and (b). Process (a) represents the capture of electrons in the GaN traps under favorable biasing and field conditions. The electron capture rate per unit volume \( r_{nc} \) depends on \( n \) (the electron concentration in the conduction band), \((N_T-n_T)\), the number of total trap states empty of electrons, and \( c_n \) the electron capture coefficient through the relation [37]–[39]:

\[
 r_{nc} = c_n n(N_T - n_T) = \sigma_n v_{th} n (N_T - n_T) \]

Where \( \sigma_n \) is the effective thermal capture cross-section of the trap to capture an electron, and \( v_{th} \) is the electron thermal velocity the product of which give the capture coefficient \( c_n \) with units of \( \text{cm}^3\text{s}^{-1} \). In contrast, the electron emission rate per unit volume \( r_{ne} \) represented by case (b) depends on \( n_T \), the number of states with electrons and the electron emission coefficient \( e_n \) through the relation [37]–[39]:

\[
 r_{ne} = e_n n_T\]
Using principle of detailed balance under equilibrium conditions, \( r_{ne} = r_{ne} \) and on rearranging terms, we get obtain the expression [7], [38], [39]:

\[
e_n = \sigma_n v_{th} n \left( \frac{N^\prime}{n_T} - 1 \right)
\]

The number of trap states \( n_T \) occupied with electrons is related to the total number of trap states through the expression [7], [38], [39]:

\[
n_T = N_T \left( 1 + \exp \left( \frac{E_T - E_F}{k_B T} \right) \right)^{-1}
\]

where \((E_T - E_F)\) is the energy of the trap level expressed with respect to the Fermi level \(E_F\), \(k_B\) is the Boltzmann constant, and \(T\) is the absolute temperature in Kelvin. Now the number of free electrons in the system \( n \) maybe expressed as [7], [38], [39]:

\[
n = N_C \exp \left( \frac{E_F - E_C}{k_B T} \right)
\]

where \(N_C\) is the conduction band density of states, \((E_C - E_F)\) is the conduction band energy expressed with reference to the Fermi level. Substituting Eqns. (2.5) and (2.4) in Eqn. (2.3), we get [7], [38], [39]:

\[
e_n = \sigma_n v_{th} N_C \exp \left( \frac{E_T - E_C}{k_B T} \right)
\]

The thermal velocity \( v_{th} \) may be expressed as [37]–[39]:

\[
v_{th} = \left( \frac{3k_B T}{m_n} \right)^{\frac{1}{2}}
\]
Where \( m_n \) is the effective electron mass. The effective conduction band density of states \( N_c \) maybe expressed as [7], [38], [39]:

\[
N_c = 2 \left( \frac{2 \pi m_n k_B T}{h^3} \right)^{3/2}
\]

where \( h \) is the Planck’s constant. Equations (2.7) and (2.8) when substituted into Eqn. (2.6) yields [7], [38], [39]:

\[
e_n = \frac{1}{\tau_n} = T^2 \gamma_n \sigma_n \exp \left( \frac{E_T - E_C}{k_B T} \right)
\]

where \( \gamma_n = \left( \frac{\nu_{th}}{T^2} \right) \left( \frac{N_c}{T^2} \right) \) is obtained by dividing out the temperature dependencies of the \( \nu_{th} \) and \( N_c \) terms. Simply taking reciprocal of Eqn. (2.9), we get [7], [38], [39]:

\[
\tau_n = \frac{1}{e_n} = \exp \left( \frac{E_C - E_T}{k_B T} \right) (T^2 \gamma_n \sigma_n)^{-1}
\]

Equation 2.10 is now in a very useful form that can be used to extract properties of a deep level such as its activation energy with respect to the conduction band \((E_C - E_T)\) expressed in eV, and its apparent thermal capture cross-section \( \sigma_n \) in units of \( \text{cm}^{-2} \). The constants \( k_B \) and \( \gamma_n \) have values \( 8.617 \times 10^{-5} \text{ eV/K} \) and \( 3.25 \times 10^{21} (m_n/m_0) \text{ cm}^{-2} \text{s}^{-1} \text{K}^{-2} \), respectively. The core principle behind any thermal based trap spectroscopy-based experiment is captured in Eqn. (2.10) which we will revisit in later sections. We use the Schottky diode based capacitance DLTS switching experiment to derive other useful results that with appropriate modification can be carried over to assessing thermally activated traps in the three terminal GaN HEMTs.
Fig. 2.2 A Schottky diode for (a) zero bias, (b) reverse bias at $t=0$, (c) and reverse bias as $t$ tends to $\infty$. The resultant capacitance transient for the applied voltage is shown in (d) (after Schroder et al. [38])
It is desired that we derive an expression for \( n_T(t) \) i.e. the occupation of electrons in the trap states as a function of time. The rate of change of occupancy of those states is the difference between the emission rate \( (r_{ne}) \) and the capture rate \( (r_{nc}) \) of electrons in the traps. Mathematically this is represented as [7], [38], [39]:

\[
\frac{dn}{dt} = e_n n_T - c_n n (N_T - n_T) \tag{2.11}
\]

Equation (2.11) represents a non-homogenous coupled nonlinear differential equation that is difficult to solve analytically. However this equation can be simplified by considering boundary conditions based on an idealized Schottky diode shown to switch from zero bias to reverse bias in Fig. 2.2. It is assumed that at time \( t = 0 \), the Schottky diode has been in zero bias for sufficiently long time such that all traps located below the Fermi level are filled to a state \( n_T(0) \). On application of reverse bias \(-V_1\) the depletion region widens. Now the previously filled traps in the depletion region occur energetically above the electron quasi-Fermi level in the bulk are emptied by means of thermal emission. During the electron emission process, the fixed charge density increases for an electron trap in n-type materials, but because the applied bias is constant, the total charge in the system should remain constant. To maintain a constant charge, the depletion depth must decrease and as the depletion region decreases, the measured capacitance increases. After sufficient duration of time it is assumed that at steady state all the traps are emptied completely, i.e. \( n_T(t = \infty) = 0 \) as is illustrated in Fig. 2.2(c) Applying this boundary conditions to Eqn. 2.11, we get:

\[
n_T(t) = n_T(0) \exp(-e_n t) \tag{2.12}
\]
From Eqn. 2.12, we expect an exponential *decrease* of trapped electron density as a function of time. The expression for capacitance as a function of time is given as:

\[
C(t) = A \sqrt{\frac{qK_s \varepsilon_0 N_D}{2(V_{bi} - V)}} \left[ 1 - \frac{n_T(t)}{N_D} \right] = C_\infty \left[ 1 - \frac{n_T(t)}{N_D} \right] \quad \text{(2.13)}
\]

Where \( A \) is the area of the Schottky diode, \( V_{bi} \) is the built-in potential, \( V \) is the applied voltage, \( K_s \) is the relative permittivity of the semiconductor, \( \varepsilon_0 = 8.854 \times 10^{-14} \text{ F/cm} \), \( q = 1.6 \times 10^{-19} \text{ C} \) is the electronic charge, and \( C_\infty \) is the capacitance of the diode under reverse bias of \( V \) in the absence of any trapping action. For \( N_T << N_D \), we apply Taylor series expansion of Eqn. (2.13) and neglect higher order terms. Also substituting Eqn. (2.12) in Eqn. (2.13), we get:

\[
C(t) = C_\infty \left[ 1 - \left( \frac{n_T(0)}{2N_D} \right) \exp \left( -\frac{t}{\tau_n} \right) \right] \quad \text{(2.14)}
\]

This equation is a mathematical approximation for the increasing exponential transient represented in Fig. 2.2(d). When these transients are recorded over a range of temperatures, the time constant \( \tau_n \) and amplitude of the transients inherently contain information about the properties of the trap causing it.

The box-car analysis technique is a well-established method to automatically record and analyze the DLTS transient data at different temperatures [7]. Figure 2.3 is an illustration of the application of box car analysis on capacitance transients. Here, two times \( t_1 \) and \( t_2 \) are chosen such that \( t_2 > t_1 \) and \( t_2/t_1 = \beta \). The difference of the capacitance transient at a given temperatures for these two times \( C(t_1) \) and \( C(t_2) \) gives rise to the DLTS signal amplitude \( \Delta C_{rw} \) given as [7]:

\[
\Delta C_{rw} = C(t_2) - C(t_1)
\]
Fig. 2.3 Schematic showing how box-car analysis at a given rate window of transients at different temperatures yields a DLTS spectrum for that rate window (After Lang [7]). At low temperatures the carrier emission from traps is too slow that the signal difference at the rate window edges gives no signal. At high temperatures the emission happens so fast that it is not captured within the time rate window used. At some intermediate temperature, the trap emission rate is resonant with the box rate window and the spectra peaks. The amplitude of the DLTS peak can be used to extract the density of the specific trap involved.
\[ \Delta C_{rw} = C(t_2) - C(t_1) = C_n \left( \frac{n_T(0)}{2N_D} \right) \left[ \exp \left( \frac{-t_2}{\tau_n} \right) - \exp \left( \frac{-t_1}{\tau_n} \right) \right] \]

The peak \( \Delta C \) is obtained when [7], [38], [39]:

\[ rw = \frac{\ln(t_2/t_1)}{t_2 - t_1} = \frac{e_n}{\tau_n} \]

where \( rw \) is the rate-window (expressed in units of s\(^{-1}\)). The DLTS peak occurs when this rate window is resonant with the emission rate Eqn (2.9). Assuming a purely exponential process, the full amplitude of the transient can be obtained from \( \Delta C \) using [7]:

\[ \Delta C = \frac{\beta^{\beta-1}}{\beta-1} \Delta C_{rw} \]

The first term is a correction factor required to obtain the full amplitude of the DLTS signal from the trap signal amplitude obtained from the rate window. Assuming that at time \( t = 0 \), all the traps are filled (i.e. \( n_T(0) = N_T \)), then the expression for bulk trap concentration \( N_T \) can be obtained using [7], [39]:

\[ N_T = 2N_D \left( \frac{\Delta C}{C_\infty} \right) \]

To obtain the thermal activation energy of the traps involved, DLTS spectra is obtained for several such rate windows to that give rise to trap peaks at different peak temperatures. This means that from different peak temperatures \( T \) we obtain the time constants \( \tau \) for a given trap from the rate window used and, resulting matrix of data can used to obtain the trap activation energy \( (E_c - E_T) \) and apparent thermal capture cross-section \( \sigma_n \), by analyzing the natural logarithm of Eqn (2.10) [7], [38], [39]:

41
Fig. 2.4 Example of (a) DLTS spectra of a single electron trap shown in different rate windows and (b) Arrhenius plot obtained from DLTS data from which trap thermal activation energy and apparent thermal capture cross-section may be extracted. ([40])
Fig. 2.5 Calculated carrier thermal emission rate as a function of temperature for deep levels with different thermal activation energies (ranging from 0.01 eV up to 1 eV) and an assumed capture cross-section of $1 \times 10^{-16}$ cm$^2$ (courtesy of Farzana et al. and Zhang et al. [40], [41]). The grey area between the horizontal dotted lines represent the typical rate windows used (at OSU) for purposes of DLTS scan. The traps with energies upto 1 eV (that lie within the grey area) have emission properties that can be adequately detected using the present experimental settings and temperature limitations. This limitation of DLTS of not being able to detected deeper traps with thermal activation energy > 1 eV serves as the motivation for optical based trap spectroscopy approaches to detect even deeper levels in wide bandgap materials.
\[
\ln(\tau_n^2) = \left(\frac{E_C - E_T}{k_B T}\right) - \gamma_n \sigma_n \tag{2.19}
\]

Such a plot of \(\ln(\tau_n T^2)\) as a function of \(1/k_B T\) is known as an Arrhenius plot and the \((E_C - E_T)\) information from such a plot is extracted from the slope of the data and the capture cross section is obtained from the y-intercept. An example of DLTS data showing a majority carrier electron trap in n-type GaN for different rate windows is shown in Fig. 2.4(a). The corresponding Arrhenius data representing that same trap is shown in figure 2.4(b). Aside from providing information about the characteristic thermal signatures of the deep level and concentrations, the sign of the DLTS signal can be used to distinguish between majority and minority carrier traps. [7],[38],[39] Multiple averaging allows very high signal to noise ratio enabling detection of trap features with densities as low as \(~5\) orders below the background doping density [7].

Despite all the advantages of DLTS, due to practical temperature stage limitations, very deep traps with activation energies > 1 eV cannot be easily detected using these methods. A better illustration of this limitation is provided in Fig. 2.5. To clearly detect a trap within a practical time range (ranging from a few hundred microseconds to a few seconds) over a temperature range of 7 K to 600 K, requires the trap to have thermal activation energies of at most 1 eV. Therefore to detect much deeper bandgap states that are well known to exist for such wide bandgap materials, it is essential that optical based approaches and this purpose is served by the DLOS family of measurements. [8],[9].
Fig. 2.6 Optically assisted emission of electrons from traps using sub bandgap monochromatic light in DLOS [40]. The filling pulse in DLOS is very similar to that already shown for DLTS in Fig. 2.2(a).

Fig. 2.7 Timing diagram showing the sequence of the DLOS experiment [40]. Immediately after the fill pulse, sufficient time is spent in the measure state in the dark to allow for the thermally active traps to emit carriers. After this process, the sample is exposed to the monochromatic light to achieve optically assisted emission. The steady state capacitance recorded as a function of different photon energies gives the DLOS spectra shown in Fig. 2.8.
2.3 Principles of optical trap spectroscopy

As is clear from the previous section, the exclusive use of thermal trap spectroscopy methods leaves behind large portions of the wide bandgap unexplored. The use of optical excitation is a powerful and effective solution to studying very deep states inaccessible to thermal methods. [8], [9] Just like in the previous section we will describe the principles of DLOS using a two-terminal n-type GaN Schottky diode [39] as example and then extend the principles to three terminal CIo-DLOS measurements in GaN HEMTs. In the Schottky diode, the deep levels are allowed first to capture electrons using a ‘fill pulse’ very similar to that shown in Fig. 2.2(b). The diode is then held in reverse bias in depletion in the dark long enough until all the thermally active traps emit electrons and the measured capacitance settles. This step required is to ensure that the DLOS results remain unadulterated by parasitic thermal transients. After this wait time, a shutter originally holding the sample in dark opens exposing the sample to sub-bandgap monochromatic light. The steady state value of capacitance \( C_{\text{steady, state}} \) is recorded for each value of photon energy \( (h\nu) \) used. An example of the resulting spectra is shown in Fig. 2.8. The onsets in the data represent the optical activation energy of the traps whereas the onset heights may be used to extract the concentration of the defects in the material using the expression [8], [9], [39]:

\[
N_p = \frac{2N_D \Delta C_{\text{steady, state}}}{C_{\infty}} \left( \frac{e_n^o(h\nu) + e_p^o(h\nu)}{e_n^o(h\nu)} \right) \]

(2.20)
Fig. 2.8 Steady state photo capacitance response showing positive onsets representing electron traps [40]. The onset energies give information of the defect’s optical activation energy and the onset heights may be used to extract the trap concentrations.

Where \(e_n(\nu)\) and \(e_p(\nu)\) are the optical emission rate of electrons and holes, respectively, from the trap of interest. When \(\nu < E_C - E_T\), the optical emission of electrons from the trap is zero and light cannot be used to empty the deep level. For light energies exceeding \(E_C - E_T\), optically assisted electron emission from the deep levels begin. The sign of the onset gives indicates the type of trap, for example in Fig. 2.8, the positive onsets represent electron traps and the onset energy represents the trap energy referred to the conduction band. For \(\nu < E_G/2\), \(e_n(\nu) = 0\), i.e. there is no optically emission of holes to the valence band from the traps whereas for \(\nu < E_G/2\), \(e_n(\nu) \neq 0\), i.e. there can simultaneously occur the competing processes of promotion of electrons to the conduction band and excitement of holes to the valence band from the same defect level. Under such conditions the trap concentration \(N_T\) extracted using DLOS is lower limit of
the actual concentration. In some cases, the onsets in the steady state DLOS spectra can be broad making the identification of exact defect levels difficult due to possible lattice relaxation effects and existence of a non-zero Franck-Condon energy \( d_{FC} \). Elaborate models by Luckovsky et al. [8], Chantre et al. [9] and many others may be applied to analyze the optical transients to extract optical cross-sections to fit and extract the true trap activation energy and the \( d_{FC} \). In the context of GaN HEMT trap spectroscopy, discussed later, the maturity of such optical cross-section models is limited and therefore trap energies will be estimated largely from energy onsets in the steady state spectrum.

### 2.4 Current-voltage expressions of AlGaN/GaN HEMTs

For a better appreciation of the effects of traps on GaN HEMT terminal IV characteristics, it is useful to briefly go through simple expressions describing the current voltage characteristics of a GaN HEMT. Figure 2.9 shows a schematic of an AlGaN/GaN HEMT where the current voltage characteristics is modulated using the gate terminal. The drain current expressions that will be derived below represent the drain current due to the ‘intrinsic’ transistor. The derivation of IV characteristics of the AlGaN/GaN HEMT follows the same principles used for other more common field effect transistors such as MOSFETs. The drain current may be obtained by integrating the sheet charge under the gate along the x-axis as shown by [42], [43]:

\[
I_{DS} = Q_{\text{sheet}}(x)Wv(x)\]

Where \( Q_{\text{sheet}}(x) \) is the 2DEG sheet charge as a function of channel position \( x \) in the intrinsic device, \( W \) is the width of the gate metal, and \( v(x) \) is the average electron velocity of the 2DEG under the gate. Taking in to account the specifics of the AlGaN/GaN
system, the expression for drain current in the triode regime ($V_{DS} < V_{GS} - V_T$) of operation of the transistor is [43]:

$$I_{DS} = \frac{1}{(1 + \mu V_{DS} / v_{sat})} \left( \frac{\mu W \varepsilon_{AlGaN}}{L d} \left[ (V_{GS} - V_T) V_{DS} - V_{DS}^2 / 2 \right] \right)$$

where $\varepsilon_{AlGaN}$ is the AlGaN dielectric constant, $L$ is the length of the gate-terminal, $d$ is the thickness of the AlGaN barrier, $v_{sat}$ is the electron saturation velocity in the GaN channel.

The expression for drain current in the saturation regime is given by [43]:

$$I_{DS} = \frac{2(V_{GS} - V_T)^2 \mu}{L d \varepsilon_{AlGaN}} \left[ 1 + \left( 1 + \xi_d \right)^{1/2} \right]$$

where $\xi_d$ is a function that determines whether the HEMT is in mobility limited or saturation velocity limited regime and is given by [43]:

$$\xi_d = \frac{2(V_{GS} - V_T) \mu}{v_{sat} L}$$

In equations (2.22-2.25) the threshold voltage $V_T$ of GaN HEMT device may be defined as [43]:
\[ V_T = \phi_B - \frac{\Delta E_C}{q} - \frac{d \cdot \sigma}{\varepsilon_{AlGaN}} - \frac{E_{fo}}{q} - \frac{d \cdot Q_{AlGaN}}{2\varepsilon_{AlGaN}} - \frac{d \cdot Q_{it}}{\varepsilon_{AlGaN}} - \frac{Q_{GaN}}{C_{\text{effective}}} \] 

where \( \phi_B \) is the Schottky gate barrier height, \( \Delta E_C \) is the AlGaN/GaN conduction band offset, \( \sigma \) is the polarization sheet charge, \( E_{fo} \) is the band bending of the GaN at the AlGaN/GaN interface referred with respect to the Fermi level (see Fig. 7.15), \( Q_{AlGaN} \) is the charge in the AlGaN barrier, \( Q_{it} \) is the charge in the AlGaN/GaN interface and \( Q_{GaN} \) is the charge in the GaN buffer.

### 2.5 Overview of constant drain-current-DLTS/DLOS (CID-DLTS/DLOS)

Having gone over the principles of DLTS and DLOS based trap spectroscopy in two terminal Schottky diodes and IV characteristics of three terminal GaN HEMTs, we now apply understanding in trap spectroscopy on two-terminal devices to three terminal GaN HEMTs. These methods applied to operational GaN HEMTs are collectively called constant current CID-DLTS/DLOS. \([24]–[36]\) Depending on the switching scheme involved, the CID-DLTS/DLOS methods may be classified into a) drain-controlled and b) gate-controlled modes. \([24]–[36]\) The drain-controlled mode is sensitive to trapping activity happening the parasitic drain access regions that affects on-resistance by impacting parasitic drain resistance \( R_D \). This trapping in the ungated regions occurs during application of large lateral electric fields resulting in the creation of a ‘virtual gate’
Fig. 2.10 Schematic illustration of sensitivity of C1D-DLTS/DLOS methods in (a) drain-controlled and (b) gate-controlled modes. Fig 2.10(c) shows how a combination of the thermal-based C1D-DLTS methods and the optical based C1D-DLOS ensures a comprehensive exploration of deep levels throughout the wide bandgap of III-Nitrides.
with much slower response times than the real metallic gate. Figure 2.10(a) schematically shows the sensitivity of the drain-controlled CI\textsubscript{D}-DLTS/DLOS methods to traps that electrostatically affect the 2DEG density outside the gate terminal and towards the drain terminal. The lateral extension of the virtual gate ($L_{\text{dep}}$) is dependent on the intensity of electric field and its dimension can be calculated (for simple Schottky gate HEMT designs) using an analytical expression [24], [30] which will be presented later. The gate-controlled mode is sensitive to traps affecting the threshold voltage $V_T$ of the transistor and from Eqn (2.25), we see that for long-channel HEMTs, $V_T$ is affect mostly by charging/discharging effects directly under the gate. As a result the gate-controlled CI\textsubscript{D}-DLTS/DLOS methods are sensitive to traps and trapping effects directly under the gate [see Fig. 2.10(b)]. Together, the gate-controlled and drain-controlled modes provide discrimination between trapping under the gate and the drain access region regions. The combination of the thermal and optical spectroscopy enables a comprehensive survey of the entire III-Nitride wideband gap for defect states as depicted in Fig. 2.10(c). Detailed description of the gate-controlled and drain controlled methods are provided in the following sections.

2.6 Drain-controlled constant current CI\textsubscript{D}-DLTS/DLOS

There have been several reports of trap impact on on-resistance changes and current collapse effects. However direct link of specific traps to observed resistance changes has been elusive. It is this objective that is realized through drain-controlled constant drain current deep level transient spectroscopy and deep level optical
Fig. 2.11 Drain controlled CI\textsubscript{D}-DLTS/DLOS switching scheme. The transistor is switched from a fill state into the triode regime which is the ‘measure’ condition where a constant drain current is maintained by dynamically controlling V\textsubscript{DS}. In this dissertation, the fill pulses used are limited to off-state moderate to high V\textsubscript{DS} ranging from 10 V to upto 600 V. For high V\textsubscript{DS} off-state fill pulses, the change in V\textsubscript{DS} for a given constant current is a measure of impact of drain access region traps on the 2DEG in the drain access region that affect R\textsubscript{ON} (and specifically the parasitic drain access resistance R\textsubscript{D}).
Fig. 2.12 Simple model representing the trap induced parasitic drain access region changes as a resistance in series with the intrinsic GaN HEMT.

Fig. 2.13 Timing diagram for drain-controlled (a) CID-DLTS, and (b) CID-DLOS

Fig. 2.13 Timing diagram for drain-controlled (a) CI\textsubscript{D}-DLTS, and (b) CI\textsubscript{D}-DLOS
spectroscopy (CI_D-DLTS/DLOS). The drain controlled switching scheme is shown in Fig. 2.11. The transistor may be switched from any given fill pulse condition. In this dissertation, however, the fill pulse has always been a pinch off state (with $V_{GS} < V_T$ always) in conjunction with a moderate to high $V_{DS}$ applied. The defining feature of the drain-controlled mode (irrespective of the fill bias) is that the ‘measurement’ always happens in the triode regime (usually with $V_{GS} = 0$ V) where a constant drain current is maintained through the GaN HEMT by dynamically controlling the drain voltage $V_{DS}$. In the triode regime, the drain current through the GaN HEMT is highly dependent on the applied drain bias across the extrinsic transistor, so if the conditions were constant voltage, the emission of charge from the virtual gate would produce a transient in drain current. However because the drain current is being maintained a constant in these methods, the $R_D$ transient of interest will be reflected entirely in the change of $V_{DS}$ as shown in Fig. 2.12. To ensure that changes in parasitic source resistance $R_S$, are minimized, the constant drain current value chosen is usually very low (<0.1 A/mm). Such low drain currents also assure minimal self-heating effects during the drain resistance transient measurements also known as ‘drain-lag’. The change in $R_D$ may be directly used as to measure of the trapping activity in the drain access regions. The drain-lag transients are recorded as a function of temperature (drain controlled CI_D-DLTS) or as a function of sub-bandgap light (CI_D-DLOS). The timing diagrams for both cases are shown in Fig. 2.13.

The CI_D-DLTS spectrum is obtained by applying box-car analysis on drain-lag transients recorded over a wide range of temperatures. The analysis give rise to peaks
with negative sign which are representative of electron traps. As described earlier, the peak temperature position for different rate windows helps in construction of Arrhenius plots from which trap signatures such as activation energy and capture cross-section may be extracted. The CI_D-DLOS spectrum is obtained by collecting the steady state drain resistance $R_D$ as a function of incident optical energy. Negative onsets in the data are representative of electron traps.

Unlike in the case of capacitance based DLTS, extraction of trap concentrations based on $\Delta R_D$ requires development of models relating drain resistance to trap concentrations. This requirement stems from the non-linear relationship between $R_D$ and trap concentrations in the drain-controlled methods. These models may be broadly classified into a) single trap model and b) multi trap model. As the name suggests the single trap model considers one kind of trap that is active in the drain access regions. The following section provides the background and salient relations in this model.

2.6.1 Single-trap model in drain-controlled CI_D-DLTS

Consider an AlGaN/GaN HEMT switched as shown in Fig. 2.13 with a single species of trap active in the drain access region. In such an experiment, at $t = \infty$ when the trap has fully emitted all electrons, the drain resistance $R_D$ of this device at (steady state) may be expressed as:

$$R_D(\infty) = \frac{L_{DG}}{qW_L m_s}$$

(2.26)
Whereas at time $t=t_p$ when the traps are filled over a dimension of length $L_{dep}$ extending from the edge of the gate, the expression of instantaneous $R_D$ would be:

$$R_D(t_p) = \frac{L_{dep}}{qW\mu(n_s - n_{T,\text{sheet}})} + \frac{L_{DG} - L_{dep}}{qW\mu n_s} \quad \text{(2.27)}$$

where $n_{T,\text{sheet}}$ is the sheet concentration of the single trap actively participating in the charge removal. The expression of change in resistance $\Delta R_D$ would be:

$$\Delta R_D = R_D(\infty) - R_D(t_p) = \frac{L_{dep}}{qW\mu} \left( \frac{1}{n_s} - \frac{1}{n_s - n_{T,\text{sheet}}} \right) \quad \text{(2.28)}$$

The value $L_{dep}$ can is extracted from an analytical transcendental expression originally developed by Rajan [44] and adapted by Arehart et al. [30]:

$$\int_0^{L_{dep}} \frac{\sigma_p}{2\pi\varepsilon} \left( \frac{x - L_{dep}}{r^2 + (x - L_{dep})^2} \right) dx - \frac{V_{DG,P}}{L_{dep}} = 0 \quad \text{(2.29)}$$

Where $V_{DG,P} = V_{DS,P} - V_{GS,P}$ is the effective voltage drop across the $L_{dep}$ region during the the drain controlled off-state high field fill pulse, $\sigma_p$ is the polarization induced sheet charge at the AlGaN/GaN interface, $r$ is the distance below the 2DEG where the electric in a direction perpendicular to it and towards the substrate, and $x$ is the distance parallel to the 2DEG originating at the gate edge and progressing towards the drain terminal. The time-transient for drain-resistance may be expressed as:

$$\Delta R_D(t) = \frac{L_{dep}}{qW\mu} \left( \frac{1}{n_s} - \frac{1}{n_s - n_{T,\text{sheet}}(t)} \right) \quad \text{(2.30)}$$

For a thermally activated trap, rewriting equation (2.12) the time response of the trap emission expressed here in terms of sheet trap concentrations is:
Fig. 2.14 Example of single trap model applied to extract trap concentration information from drain-controlled CI\textsubscript{D}-DLTS data Figure 2.14(a) shows real data for a single trap detected in the drain access region of a MOCVD grown GaN HEMT. Data is fitted to a simulation using a trap spectra shown in 2.14(b) the peak of which gives the estimate of the trap concentration. The model thus enables quantitative estimation of trap concentration from drain-controlled CI\textsubscript{D}-DLTS methods.
\[ n_{T,\text{sheet}}(t) = n_{T,\text{sheet}}(0)\exp(-e_n t) \] 

Where expression for \( e_n \) was already provided in Eqn (2.9). Using expressions (2.9), (2.30), and (2.31), drain controlled \( \text{Cl}_\text{D}-\text{DLTS} \) simulations were generated. These simulated data when fit to measured drain-controlled \( \text{Cl}_\text{D}-\text{DLTS} \) data representing a single trap provides an estimate for the concentration of traps in the drain-access region. A demonstration of such a fit is shown in Fig. 2.14(a). The measured and simulated drain-controlled \( \text{Cl}_\text{D}-\text{DLTS} \) data is plotted for the 80 s\(^{-1}\) rate window. The goodness of fit of the simulated plot is controlled using the choice of \( n_{T,\text{sheet}} \) alone. The trap energy and capture cross-section of the single trap being evaluated was already extracted separately from the measured drain controlled \( \text{Cl}_\text{D}-\text{DLTS} \) data using the Arrhenius analysis. Box car analysis of the simulated trap occupation transient given by Eqn. (2.31), is plotted for rate window 80 s\(^{-1}\) in Fig. 2.14(b). The trap density \( n_{T,\text{sheet}} \) for the single trap is simply read off the peak of this plot.

### 2.6.2 Single-trap model in drain-controlled \( \text{Cl}_\text{D}-\text{DLOS} \)

To obtain trap concentrations of a single species of trap from drain controlled \( \text{Cl}_\text{D}-\text{DLOS} \), spectrum we rearrange Eqn (2.28) to give the expression:

\[ n_{T,\text{sheet}} = \frac{n_s^2}{n_s - \frac{L_{\text{dep}}}{qW\mu\Delta R_{\text{D}}}} \] 

Where \( \Delta R_{\text{D}} \) is the onset in the steady state drain resistance observed as a function of incident sub-bandgap photon energy.
The single trap models for drain-controlled CI-DLTS and CI-DLOS are useful for making first-order surveys of trapped charge in the drain access regions of GaN HEMTs. However, the single trap models for both CI-DLTS and CI-DLOS suffer from the same limitation which is the assumption that all the trapping effects happening in the virtual gate of the transistor are due to a single defect species with a single trap energy. If on the contrary if multiple traps were to exist (which is more realistic) and actively participate in the drain access region to affect $R_D$, the single trap model cannot be applied. Judging from Eqns. (2.30) and (2.32), the non-linear relationship between $n_{T,sheet}$ and $R_D$ will make trap concentration extraction and data interpretation very difficult in such multi-trap cases making it necessary to develop the multi-trap model described next.

2.6.3 Multi-trap model in drain-controlled CI-D-DLTS

In the more elaborate multi-trap model, we consider a general case of $N$ distinct electron traps active in the drain access regions of the GaN HEMT with thermal activation energies of $E_{T,1}$, $E_{T,2}$, $E_{T,3}$……$E_{T,K}$,………, and $E_{T,N}$ referred to the the conduction bandedge $E_C$. The thermal capture cross-sections of these traps are, respectively, $\sigma_{n,1}$, $\sigma_{n,2}$, $\sigma_{n,3}$, …, $\sigma_{n,k}$, …, and $\sigma_{n,N}$. Let us assume the concentrations of these traps when completely filled with electrons at time $t=t_p$ to be $n_{T,sheet 1}(0)$, $n_{T,sheet 2}(0)$,…………$n_{T,sheet k}(0)$, …………….., $n_{T,sheet N}(0)$. The expression for the thermal emission for the $k^{th}$ trap at given temperature $T$ with trap emission trime constant $e_{n,k}(T)$ is given as:

$$n_{T,sheet k}(t,T) = n_{T,sheet k}(0)[\exp(-e_{n,k}(T)t)]^{....................}(2.33)$$
Where $e_{n,k}$ is the trap emission rate of the $k^{th}$ trap at temperature $T$ given as:

$$e_{n,k} = \gamma n \sigma_{n,k} T^2 \exp\left(\frac{E_{T,k} - E_C}{k_B T^2}\right)$$

Likewise each trap $E_C - E_{T,1}, E_{T,2}, E_{T,3}, \ldots, E_{T,k}, \ldots, E_{T,N}$ has a thermal emission rate $e_{n,1}, e_{n,2}, e_{n,3}, \ldots, e_{n,k}, \ldots, e_{n,N}$ such that $e_{n,1} > e_{n,2} > e_{n,3} > \ldots > e_{n,k} > \ldots > e_{n,N}$. This means that $E_C - E_{T,1}$ eV is the fastest electron emitting strap and $E_C - E_{T,N}$ is the slowest one. In this situation, the local 2DEG density $n_S$ in the virtual gate at a given temperature $T$ is given as:

$$n_s - n_{\text{t,sheet tot}} = n_s - \left[n_{\text{t,sheet } 1}(0)[\exp(-e_{n,1}(T)t)] + \ldots + n_{\text{t,sheet } N}(0)[\exp(-e_{n,N}(T)t)]\right] \ldots (2.35)$$

We assume that at temperature $T$, the $k^{th}$ trap is activated. This means that in all the slower trap $E_C - E_{T,k+1}$ to $E_C - E_{T,N}$ the electrons are ‘frozen’ in and all the fast traps $E_C - E_{T,1}$ to $E_C - E_{T,k-1}$ have already emitted electrons through thermal excitation. Assuming this the effective 2DEG density now becomes:

$$n_{s,\text{eff}} = n_s - \left[n_{\text{t,sheet } k+1}(0)[\exp(-e_{n,k+1}(T)t)] + \ldots + n_{\text{t,sheet } N}(0)[\exp(-e_{n,N}(T)t)]\right] \ldots (2.36)$$

In other words, the effective 2DEG density within the virtual gate is diminished by the presence of slowly emitting traps. Such a reduction in the $n_S$ would cause an amplification of the drain-lag $\Delta R_D$ signal related to the $k^{th}$ trap through the non-linear relation:

$$\Delta R_D(t) = \frac{L_{\text{dep}}}{qW\mu} \left\{\frac{1}{n_{s,\text{eff}}} - \frac{1}{n_{s,\text{eff}} - n_{\text{t,sheet } k}(t)}\right\}$$

\[\vdots (2.37)\]
Fig. 2.15. Example of multi trap model applied to extract of trap concentration information from drain-controlled CI-D-DLTS data. Drain controlled CI-D-DLTS thermal spectra (solid) for 80 s⁻¹ rate window of a N-polar MOCVD GaN HEMT showing two dominant virtual gate electron traps with activation energies $E_C$–0.54 eV and $E_C$–0.65 eV virtual gate electron trap and simulated (dotted) drain-controlled CI-D-DLTS spectra with best fit to the measured data. (b) $n_T$ DLTS plots extracted from the fit shown in Fig 2.15(a) where green and black peaks give concentrations of the $E_C$–0.65 and $E_C$–0.54 eV traps, respectively. Unlike what the $\Delta R_D$ plots suggest where the $E_C$–0.65 eV trap $\Delta R_D$ is greater than the $E_C$–0.54 eV trap $\Delta R_D$, it is the $E_C$–0.54 eV trap that has a higher trap concentration (~6x more than $E_C$–0.65 eV trap) making it in reality the dominant trap in this HEMT.
Fig. 2.16 Measured CI_D-DLTS and simulated CI_D-DLTS considering (a) only the $E_C-0.65\text{ eV}$ trap and (b) only the $E_C-0.54\text{ eV}$ trap. Without the influence of the $E_C-0.54\text{ eV}$ trap the $E_C-0.65\text{ eV}$ level has practically no impact on the drain-controlled CI_D-DLTS amplitudes and the fitting to measured data is poor through the entire time/temperature range. From Fig 2.16(b), we observe that absence of the faster $E_C-0.65\text{ eV}$ trap does not influence the slower $E_C-0.54\text{ eV}$ trap $\Delta R_D$. This means that slow traps affect $\Delta R_D$ of fast traps by diminishing local $n_s$ but the converse is not true i.e. fast traps have no bearing on the $\Delta R_D$ magnitude of slower traps.
Where $n_{s,\text{eff}}$ is the updated 2DEG density obtained from Eqn (2.36). The Eqn. (2.37) mathematically describes the non-linear effect wherein the presence of a slower frozen in trap can impact the $\Delta R_D$ signatures of a faster trap. This phenomenon can be confusing at best and misleading at worst when dealing with $\Delta R_D$ signals to extract or ascertain relative presence of multiple traps in the drain access regions of a GaN HEMT. This anomaly is best illustrated by means of an example. We use drain-controlled CI-D-DLTS data collected [Fig. 2.15(a)] from an N-polar MOCVD grown GaN HEMT to demonstrate the multi-trap effect in the drain controlled CI-D-DLTS. The two prominently detected traps in this HEMT have activation energies of $E_C-E_{T,1}=0.65$ eV and $E_C-E_{T,2}=0.54$ eV with thermal capture cross-sections of $\sigma_{n,1}=2\times10^{-13} \text{ cm}^2$ $\sigma_{n,2}=7\times10^{-16} \text{ cm}^2$, respectively. Using Eqn (2.34) we determine that at any given temperature the $E_C-0.65$ eV emits electrons $\sim 15x$ faster (with $\tau_1 \sim 2$ ms at $T=300\text{K}$) than the $E_C-0.54$ eV trap (with $\tau_2 \sim 30$ ms at $T=300\text{K}$). This means that when evaluating the $\Delta R_D$ transient associated with the $E_C-0.65$ eV trap, all the slower traps (in this case the $E_C-0.54$ eV trap) have to be accounted for in the $n_s$ value of $8.5\times10^{12} \text{ cm}^{-2}$ which effectively reduces $n_s$ to a lower value $n_{s,\text{eff}} = n_s-n_{s,\text{sheet}} z(0)$. Having carefully accounted for these effects in Eqn. (2.36), a drain-controlled CI-D-DLTS plot is simulated (dotted line in Fig. 2.15(a)) that shows best fit to the measured drain-controlled CI-D-DLTS data. The trap concentrations of individual traps used to obtain this fitting are shown in Fig 2.15(b). In stark contrast to Fig. 2.15(a) where the $\Delta R_D$ of the $E_C-0.65$ eV trap was larger and therefore $E_C-0.65$ eV appeared dominant, it is the $E_C-0.54$ eV that is present in larger concentrations (~6x larger) than the $E_C-0.65$ eV trap making it in reality the dominant trap. The amplification
of the Ec–0.65 eV trap ΔRD peak at ~275 K was a result of reduction of the local 2DEG density in the virtual gate ns due to electron freeze out at that temperature in the Ec–0.54 eV trap thereby effectively reducing the local 2DEG density ns to \( n_{s,\text{eff}} = 8.5 \times 10^{12} - 6.8 \times 10^{12} \text{ cm}^{-2} = 1.7 \times 10^{12} \text{ cm}^{-2} \). This means that even a small modulation of the Ec–0.65 eV trap density (of 1.1 \times 10^{12} \text{ cm}^{-2}) can result in a large ΔRD through the non-linear effects. This fact is clear from Fig. 2.16(a) where only the Ec–0.65 eV trap has been considered and the Ec–0.54 eV trap effects have been neglected in the simulations. The ΔRD signal from the Ec–0.65 eV is almost negligible because of its low concentration that is insufficient to impact the large 2DEG density of 8.5 \times 10^{12} \text{ cm}^{-2} that remains unchanged at 275 K because no slow traps freeze-out was considered in this simulation. However the converse is not true i.e. the faster Ec–0.65 eV cannot impact the ΔRD of the slower Ec–0.54 eV trap and this is illustrated in Fig. 2.16(b). This example demonstrates the non-linear and somewhat non-intuitive relationship between \( n_{T,\text{sheet}} \) and ΔRD and impact on interpretation of ΔRD signals which is why it is necessary to have such rigorous model dedicated to extraction of trap concentration from drain-controlled ClD-DLTS measurements.

2.6.4 Multi-trap model in drain-controlled ClD-DLOS

In case of drain controlled ClD-DLOS, sub-bandgap light is used to promote electron from deep states to the conduction band. In the presence of light the removal of negative charges from traps causes an increase in ns. The original ns was measured using Hall measurements at 300 K in the dark. This \( n_s \) should already incorporate the presence
of all pre-existing deep traps in the system. The effective \( n_s \) just before the \( k^{th} \) trap in an N-trap system is optically excited during drain controlled CID-DLOS analysis is:

\[
n_{s,\text{eff.}} = n_s + \left( n_{T,\text{sheet}}(0) + \ldots + n_{T,\text{sheet} \ k^{-1}}(0) \right)_{\text{eff}} \] (2.38)

All traps \( E_C-E_{T,1} \) through \( E_{T,k-1} \) have been ionized using light with energy \( h\nu > E_C-E_{T,k-1} \).

The expression to evaluate the individual trap concentration \( n_{T,\text{sheet} \ k} \) for the \( k^{th} \) trap is given by:

\[
n_{T,\text{sheet} \ k} = \frac{n_s^2}{n_{s,\text{eff}} - \frac{L_{\text{dep}}}{qW\mu\Delta R_{D,k}}} \] (2.39)

Where \( \Delta R_{D,k} \) is onset height of the drain controlled CID-DLOS spectra for the \( k^{th} \) trap.

Using the multi-trap model in the CID-DLTS/DLOS, the individual concentrations of deep levels causing \( R_D \) changes in GaN HEMTs can be correctly and quantitatively evaluated.

Development of these multi-trap models for drain-controlled CID-DLTS and CID-DLOS in the context of drain-access region trapping of GaN HEMTs has provided a deeper physical insight into the non-linear relation between trap concentrations and drain resistances and their manifestation into transistor terminal characteristics. This phenomenon is common to all HEMT-based trap spectroscopy methods sensitive to traps in the access regions and therefore must be carefully accounted for before quantitative discussions regarding trap concentrations are attempted.
2.7 Gate controlled constant current $C_{ID}$-DLTS/DLOS

The main objective of the gate-controlled $C_{ID}$-DLTS/DLOS method is to identify specific traps located under the gate that affect the threshold voltage $V_T$ in operational HEMT devices. To do so any effects from the parasitic access regions have to be minimized. To ensure both these conditions are satisfied, gate-controlled measurements (irrespective of the fill pulse) are always made in the saturation regime with low drain current flowing as shown in Fig. 2.17. Being in the saturation regime, the GaN HEMT (provided it has low output conductance) should be insensitive to changes in drain resistance (if any) during the gate-controlled switching. Depending on the $V_T$ phenomenon that is of interest, the GaN HEMT may be switched from on-state to the low current saturation regime OR from an off-state moderate to high $V_{DS}$ state to the saturation regime. Figure 2.18 shows the timing diagrams for an off-state moderate to high $V_{DS}$ fill pulse case for the gate-controlled mode. The gate voltage $V_{GS}$ is dynamically controlled to maintain a constant but low ($<0.01$ A/mm) drain current through the transistor. Repeating the Eqn. (2.23) as a function of time in gate-controlled constant current mode we get:

$$I_{DS} = \frac{2[V_{GS}(t) - V_T(t)]^2 W_E_{AlGaN} \mu}{L_d} \left[ 1 + \left( \frac{L}{d} \right)^{1/2} \right]^2 \text{..............................(2.40)}$$

Here all terms in the equation are invariant as a function of time except for $V_{GS}(t)$ and $V_T(t)$, therefore any measured change in $V_{GS}$ should be a direct measure of $V_T$ change due to traps everything else being constant i.e. $\Delta V_{GS} = \Delta V_T$. Even before extracting trap information, this is an important result because there is great utility in the ability to extract $V_T$, a real device parameters as a function of time, temperature and incident light energy.
Fig. 2.17 Gate controlled C\textsubscript{ID}-DLTS/DLOS switching scheme. The transistor is switched from a fill state into a ‘measure’ state in the saturation regime a constant drain current is maintained by dynamically controlling \( V_{GS} \). The change in \( V_{GS} \) after a fill pulse recorded for a given constant current is a measure of impact of under gate traps on threshold voltage \( V_T \) of the GaN HEMT under test.

Fig. 2.18 Timing diagram for gate-controlled (a) C\textsubscript{ID}-DLTS, and (b) C\textsubscript{ID}-DLOS.

Fig. 2.18 Timing diagram for gate-controlled (a) C\textsubscript{ID}-DLTS, and (b) C\textsubscript{ID}-DLOS.
Expressing Eqn (2.25) as a function of time we get:

\[ V_T(t) = \phi_B - \frac{\Delta E_C}{q} - \frac{d \cdot \sigma}{\varepsilon_{AlGaN}} - \frac{E_f - \frac{d \cdot Q_{AlGaN}(t)}{2\varepsilon_{AlGaN}}}{\varepsilon_{AlGaN}} - \frac{Q_{GaN}(t)}{C_{\text{effective}}}. \] ......(2.41)

The changes occurring in \( V_T \) could be due to under-gate trapping effects occurring in the AlGaN, interface, or GaN buffer. All other terms in the equation should be constant as a function of time. Suppose we assume all the traps (a total sheet concentration of \( n_{T,\text{sheet}} \)) in the AlGaN barrier. The expression for \( \Delta V_T \) in Fig. 2.18 based on Eqn. (2.41) becomes:

\[ \Delta V_T(t) = -\frac{d \cdot qn_{T,\text{sheet}}(t)}{2\varepsilon_{AlGaN}}. \] ..................(2.42)

Rearranging terms in Eqn (2.42), we get a linear relationship between under-gate trap concentration \( n_T(t) \) and threshold voltage transient \( V_T(t) \). Having established a direct and linear relationship between \( V_T \) transients and trap concentration transient \( n_T \), from this point on simple box-car analysis of \( V_T(t) \) time transients yield gate-controlled CI_D-DLTS transients just as described for capacitance DLTS. The Arrhenius analysis of the gate-controlled CI_D-DLTS peaks for different rate windows gives information of the particular trap energy and capture cross-section. Negative gate-controlled CI_D-DLTS peaks represent electron traps by conventions and the activation energies extracted are referred to the conduction band edge. Unlike drain-controlled CI_D-DLTS, the relations between \( V_T \) and \( n_{T,\text{sheet}} \) are linear and straightforward and therefore no special model is required for extract of trap concentrations whether there are single or multiple species of traps active under the gate. The analysis of the gate-controlled DLOS is also very similar to that
described in the capacitance DLOS described earlier. The only difference here is that the steady state photo voltage \([V_{GS,SS}\text{ shown in Fig. 2.18(b)}]\) is recorded as a function of incident monochromatic sub-bandgap light. Negative onsets in the data are indicative of electron traps and the optical activation energies obtained from the onset are referred from the bottom of the conduction band edge. The onset heights may be used to extract the individual trap concentrations. Once again unlike the drain-controlled mode, because of the linear relationship between \(\Delta V_T\) and \(n_T\) individual trap concentrations of multiple traps in the system can be extracted directly from the \(\Delta V_T\) plot without the need for any rigorous modeling.

The expression for trap concentration extraction from both gate-controlled ClD-DLTS and ClD-DLOS is obtained by rearranging Equation (2.42) as follows:

\[
n_{T,\text{sheet}} = -\frac{2\varepsilon_{AlGaN}}{d \cdot q \Delta V_T} \tag{2.42}
\]

Where \(\Delta V_T\) is obtained from amplitude of the corresponding trap peak in gate controlled ClD-DLTS or from the onset height of the deep level in the gate-controlled ClD-DLOS.
2.8 Supporting characterization techniques

2.8.1 Pulsed IV

In addition to DC IV measurements, synchronous double pulsed IV measurements were made possible using Accent opto DiVA system and a Keithley 4200 SDA. The pulse durations were as low as 200 ns with duty cycles of <1% to minimize self-heating effects. Pulsed IV measurements were made both in $I_D-V_{DS}$ and $I_D-V_{GS}$ modes using the Keithley SDA. Pulsed IV measurements offer a superior alternative to DC IV because of minimal self-heating effects. Differences in pulsed IV in HEMTs as a function of stressors can give a qualitative measure of the type of degradation (see Fig. 2.19) and informs the more advanced CID-DLTS/DLOS efforts.

2.8.2 nano-DLTS/DLOS

The nano-scale DLTS/DLOS (see Fig. 2.20) is a highly localized high spatial resolution atomic force microscopy (AFM) based spectroscopy of defects using surface potential transients recorded as a function of time, temperature, or sub-bandgap monochromatic light. [45]–[47]. The surface potential transients are measured in an operational HEMT device while its terminal voltages are switched using function generators. Custom built AFM control apparatus is used to monitor the voltage $V_{sp}$ required to maintain the AFM tip from touching the surface. This $V_{sp}$ should be independent of traps beneath the 2DEG that acts as a ground place. The exploitation of the high vertical and lateral sensitivity of the method will be discussed in Chapters 4 and 6 where 3D-trap spectroscopy was performed to unambiguously locate the physical position of two traps within the GaN buffer.
Fig. 2.19 Pulsed IV before and after a stressor qualitatively captures all the static (switching independent) and dynamic (switching dependent) degradation effects of the stressors minus any self-heating effects that may occur during the DC IV measurements.

Fig. 2.20 Schematic representation of the nano-scale DLTS/DLOS setup After (Cardwell [45]). The AFM probe records the local surface potential transients as a function of switching of the transistor using two function generators connected each to the drain and the gate. The temperature stage enables recording of $V_{sp}$ at different temperatures. The fiber optic cable deliver ~1.2 eV to >4.3 eV light from a Xe lamp, monochromator system to the sample. Custom built software and circuitry is used to control the switching, thermal, and optical components of this system.
2.9 Summary and Conclusions

This chapter offers a survey of the major electrical and optical characterization techniques and models employed in this dissertation work, namely constant drain current CID-DLTS and DLOS. These techniques are based on the influence of deep level charge trapping and detrapping on GaN HEMT terminal characteristics such as on-resistance and threshold voltage, so the underlying fundamentals of these methods were presented. In addition to CID-DLTS/DLOS methods, a discussion of supporting trap characterization techniques such as nano-DLTS/DLOS, and pulsed IV were provided. It is the appropriate application of the CID-DLTS/DLOS methods in combination with these supporting techniques that allow to track the traps, determine their location (wherever possible) and obtain a deeper understanding of their properties in the operational GaN HEMTs as a function of different designs and/or operational history.

2.10 References


Chapter 3

Application of CI_D-DLTS/DLOS methods and models to RF stressed GaN HEMTs

3.1 Introduction

While unprecedented levels of RF performance has been achieved using GaN HEMTs, the combination of high electric fields, high current densities and high temperatures that represent the conditions for GaN HEMTs in their ultimate applications creates challenges for understanding the pathways in which GaN HEMTs degrade, and more generally, the predictability of reliability [1]-[6]. Accelerated life testing (ALT) of GaN HEMTs has revealed a reduction in RF output power $P_{\text{out}}$ as a function of ALT stress, [5], [6] there has been considerably more reports of catastrophic failure wherein pits form at the gate edge of the drain access region [7], [8]. As already mentioned in Chapter 1, current thinking suggests that the underlying cause of such degradation and failure involve the formation, activation or movement of electrically active defects within the AlGaN/GaN heterostructure (or its various interfaces), with such defects behaving as charge trapping centers [5], [6], [9]-[15]. The presence (or absence) of these traps could therefore determine the reliable operational lifetime of a particular RF GaN HEMT, as well as the particular
mechanism for device failure. It is therefore important to detect and monitor the electronic behavior of such defects, in a meaningful and quantifiable fashion, within operational RF devices. In Chapter 2 we discussed an advanced suite of techniques and models based on constant current deep level transient and optical spectroscopy (CID-DLTS/DLOS), that reveal and track the evolution of individual defect (trap) energy levels, their concentrations and cross-sections, within fully operational HEMTs without the need for fabricating specialized test structures [18]–[22]. We also mentioned that through appropriate biasing schemes the CID-DLTS/DLOS methods discriminate between under-gate traps and traps present in the ungated (or access) regions of a HEMT [18]–[22]. In this chapter, we discuss the application of these advanced trap spectroscopy measurements GaN based commercial HEMTs optimized for X-band RF operation. The HEMTs were subjected to accelerated RF stressing and the dominant traps in the HEMTs before and after the stressing was carefully monitored. It was observed that a particular electron trap at $E_C-0.57$ eV trap seems to directly correlate or track with the observed increase in RF degradation. The rest of the chapter provide a detailed description of the samples and the experimental results and discussion associated with this stressing campaign.

<table>
<thead>
<tr>
<th>Vendor</th>
<th>HEMT A</th>
<th>HEMT B</th>
<th>HEMT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor</td>
<td>Vendor1</td>
<td>Vendor2</td>
<td>Vendor2</td>
</tr>
<tr>
<td>Gate periphery</td>
<td>1.25 mm</td>
<td>0.4 mm</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Max. RF P_{out}</td>
<td>3.2 W/mm</td>
<td>2.5 W/mm</td>
<td>2.5 W/mm</td>
</tr>
<tr>
<td>Class AB DC operating point</td>
<td>$V_{DS} = 48$ V, $I_{DS} = 100$ mA/mm</td>
<td>$V_{DS} = 35$ V, $I_{DS} = 205$ mA/mm</td>
<td>$V_{DS} = 35$ V, $I_{DS} = 205$ mA/mm</td>
</tr>
</tbody>
</table>

Table 3.1 Specifics of the GaN HEMTs A, B, and C presented in Chapter 3
Table 3.2 Accelerated life testing conditions for the HEMTs A, B, and C

<table>
<thead>
<tr>
<th></th>
<th>HEMT A</th>
<th>HEMT B</th>
<th>HEMT C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel temp.</td>
<td>Vendor1</td>
<td>Vendor1</td>
<td>Vendor2</td>
</tr>
<tr>
<td>RF Pin</td>
<td>29 dBm</td>
<td>23 dBm</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>10 GHz</td>
<td>10 GHz</td>
<td>10 GHz</td>
</tr>
<tr>
<td>ALT duration</td>
<td>664 hours</td>
<td>1197 hours</td>
<td>4041 hours</td>
</tr>
<tr>
<td>Pout drop@Pin</td>
<td>1 dB</td>
<td>1 dB</td>
<td>No degradation</td>
</tr>
</tbody>
</table>

Fig. 3.1 RF output power as a function of ALT stress time (log scale) for three MOCVD GaN HEMTs with stressing conditions listed in Table 3.2. HEMTs A and B show 1 dB drop in $P_{out}$ within ~410 hr of ALT whereas HEMT C showed no measurable degradation despite >4000 hr of ALT.
3.2 Sample information

The AlGaN/GaN HEMTs studied in this work were grown using metal organic chemical vapor deposition (MOCVD) and obtained from two commercial vendors denoted as Vendor 1 and Vendor 2 [19], [20]. Three separate HEMTs were studied in this work. HEMT A was supplied by commercial Vendor 1. HEMTs of type B and C came from Vendor 2. All three HEMTs where grown on SiC substrate and passivated in the access regions using SiNₓ. All the HEMTs presented in this study have ~20 nm AlGaN barriers with ~25% Al mole fraction. The devices had had source connected field plates optimized for X-band operation. More information of these three transistors are summarized in the Table 3.1.

3.3 RF accelerated life testing and results

The HEMTs A, B, and C were RF stressing using conditions listed in Table 3.2. The RF output power (P_{out}) of these HEMTs degraded as a function of stressing time as shown in Fig. 3.1. Of the three HEMTs, two of them, namely HEMTs A and B degraded in terms of RF output power by 1 dB in a relatively short period of electrical stressing (within ~410 hours). The HEMT C however was far more robust and survived 4041 hours of RF electrical stressing whilst showing no measureable degradation. What we have here is an interesting set of results wherein then HEMTs A and B from different vendors show a very similar trend in RF P_{out} degradation whereas HEMTs B and C from the same vendor show very different degradation trends. In order to clearly identify the root cause of differences within a vendor series (and similarities across different vendor
series) standard IV characterization was performed and followed up HEMT-based trap spectroscopy experiments.

3.4 Motivation to perform drain access-region sensitive defect spectroscopy

The measured threshold voltage shift $V_T$ in all three HEMTs before and after the RF stressing was very small ($< 50$ mV). This observation suggests that the formation/activation of electrically active defects under the gate during the RF stressing is limited. This conclusion is consistent with the knowledge that during the accelerated RF life testing process, large $V_{DS}$ values are applied which in turn causes large electric field build up at the edge of the gate closest to the drain terminal. The presence of source connected field plates in these HEMTs, would further tend to push the high fields and associated trapping possibility further from the gate and more into the drain access region. Given all these facts, the drain-controlled HEMT trap spectroscopy methods were the appropriate tools to probe for access region (especially drain access region defects) that could be forming/activating during the RF stressing process. The experimental details of these measurements are described next.

3.5 Drain controlled $C_I D$-DLTS experimental conditions

All HEMTs in this study were switched from off-state $V_{GS}<V_T$ and $V_{DS} = 15$ V applied for 100 ms to triode region with $V_{GS} = 0$ V and a constant $I_{DS} \sim 0.1$ A/mm. The drain voltage $V_{DS}$ was dynamically controlled using a custom built feedback circuit to realize the constant drain current. As already explained in Chapter 2, the change in $V_{DS}$
Fig. 3.2 Drain controlled CI\textsubscript{D}-DLTS spectra for 2000 s\textsuperscript{-1} rate window showing a dominant Ec–0.57 eV electron trap in all three HEMTs. The concentration of this trap increases in the HEMTs A and B that showed the 1 dB degradation in \( P_{\text{out}} \). However in HEMT C that did not degrade as a function of ALT not only did the Ec–0.57 eV not change but it also was lower compared to the HEMTs A and B indicating that the quantity of this trap could serve as a predictor of device lifetime.
Fig. 3.3 Arrhenius plot extracted from drain-controlled CI_D-DLTS measurements on HEMTS A, B, and C before and after ALT. The Arrhenius data of the dominant trap shows excellent overlap for all three HEMTs suggesting that it is a common defect. No change is observed in the thermal activation energy (i.e. $E_c$=0.57 eV) of this defect before and after ALT.

$E_c = 0.57 \pm 0.05$ eV

$\sigma_n \sim 0.5$ to $3 \times 10^{-15}$ cm$^2$
is converted to change in on-resistance (in this cases drain resistance) using a simple relation [18]–[22]:

\[ \Delta R_D = \frac{\Delta V_{DS}}{I_{DS,\text{const}}} \]  

This \( \Delta R_D \) transient collected for a given temperature is called a ‘drain-lag’. The CI\(_D\)-DLTS is simply a result of the box-car analysis of such drain-lag transients collected over a wide range of temperatures. As already described in Chapter 2, the negative peaks are indicative of electron traps and the amplitudes of which can be used to extract trap concentration using Eqn. 2.1.

### 3.6 Drain controlled CI\(_D\)-DLTS results

The drain-controlled CI\(_D\)-DLTS results from the three AlGaN/GaN HEMTs, A, B, and C are presented in Figure 3.2. From the Arrhenius analysis shown in Fig. 3.3, it is clear that all the HEMTs showed the signature of an Ec–0.57 eV trap prior to any stressing. The capture cross section of the trap is \( \sim 5 \times 10^{-15} \text{ cm}^2 \). The concentration of the Ec–0.57 eV trap before stressing ranged between 3.8 and 5.8 \( \times 10^{12} \text{ cm}^{-2} \). Of the three HEMTs investigated in this study, HEMT C from Vendor 2 has the lowest Ec–0.57 eV trap concentration pre-stressing.

After the RF stressing, we start observing key differences in the formation/activation of the Ec–0.57 eV that apparently tracks the RF Pout degradation trends of the three HEMTs. In the HEMTs A and B from, vendors 1 and 2 respectively, that showed the output power drop by 1 dB, the Ec–0.57 eV trap concentration in the drain access region increased by 1.8 to 2.7 \( \times 10^{12} \text{ cm}^{-2} \). In stark contrast, the HEMT C
Fig. 3.4 (a) The drain-lag transient data at different temperatures are fitted with a single exponentially decaying time-constant function expressed as dotted lines in figure, (b) Arrhenius data (closed circles) collected from the drain-lag transients show excellent match with the Ec–0.57 eV Arrhenius data collected from drain-controlled ClD-DLTS suggesting that the Ec–0.57 eV trap concentration increase is what caused the dynamic RD increase in the HEMTs A and B.
from vendor 2, showed no increase in concentration of the Ec–0.57 eV trap concentration. What is observed is a direct link between the occurrence of the Ec–0.57 eV trap and the state of degradation of the HEMT irrespective of the Vendor. The Ec–0.57 eV trap concentration increase is the only common occurrence in HEMTs A and B from different vendors. The HEMT C, which originally had the lowest concentration of the Ec–0.57 eV trap, however, showed no increase in concentration of this defect. The same HEMT C showed no drop in RF output power (see Fig. 3.1) despite the fact that this HEMT came from the same vendor as HEMT B. These results establish a causality and directly connection of the Ec–0.57 eV trap to RF degradation in AlGaN/GaN HEMTs. The next step was to identify the mechanism by means of which this trap affected the HEMT terminal IV characteristics and degraded the RF performance.

3.7 Directly correlating the drain-lag effect to Ec–0.57 eV trap

To further understand the role of this in device degradation, drain lag measurements were made at different temperatures. Figure 3.4(a) shows drain-lag results from HEMT C after RF stressing (identical trends were observed in HEMTs A and B), which reveal a temperature dependent exponential decay time constant of 30 ms at room temperature. The drain-lag transients collected at different temperatures were used to generate Arrhenius data shown as red solid circles in Fig 3.4(b). The open circles represent the Arrhenius data of the Ec–0.57 eV trap extracted from the ClD-DLTS measurements. The two sets of Arrhenius data overlap proving that the Ec–0.57 eV is responsible for the observed 30 ms time-constant drain lag at room temperature. This finding directly correlates the a transistor terminal phenomenon such as drain lag to a trap in the material system,
Fig. 3.5 Drain-lag switching transients with a decay time constant ~30 ms when measured at 300 K using conditions described in the section 3.6. The HEMT B shows an increase in dynamic drain resistance post-ALT whereas the resistance of the HEMT C is lower than that of HEMT B before and after the RF stressing.
3.8 Mechanism of E_C-0.57 eV induced HEMT performance degradation

In order to describe the role of this particular trap on HEMT switching characteristics, drain-lag data was collected from HEMTs B and C as shown in Fig. 3.5. The drain-lag data trends from HEMT A are similar to those represented by HEMT B and for sake of clarity are not shown. As is clear from this plot, the drain-lag transient also known as dynamic drain resistance of the HEMT B is \( \sim 6x \) greater than it was before the RF stressing. This increase in dynamic drain resistance leads to collapse of drain current in the triode regime that subsequently causes a walkout in the knee of the output IV characteristics. The increase in knee walkout restricts the output voltage swing (for times shorter than 30 ms at room temperature). This restriction in output voltage swing is what ultimately causes the drop in RF output power. In this manner, traps formation/activation can directly play a role in the degradation of RF performance characteristics. Unlike HEMTs A and B, HEMT C shows no change in drain-lag i.e. its dynamic drain-resistance remains unchanged as a function of stressing. This means that no additional knee walkout occurred in this particular HEMT as a result of which no restriction was imposed on the maximum voltage swing during the RF switching. This is why no output power degradation was observed in HEMT C despite prolonged RF stressing. Once again we have shown the direct causality of the increase of the E_C–0.57 eV trap and how it is linked to an increased drain-lag effect in the transistors that serves as the mechanism for the RF output power degradation.
3.9 Optically detected deep traps and their possible role in the
RF degradation of these HEMTs

The Ec–0.57 eV level is not the only trap observed in the drain-access regions of these HEMTs. Several other deeper levels were detected in these devices by means of drain-controlled deep level optical spectroscopy (ClD-DLOS) that circumvents the thermal emission limits of ClD-DLTS by substituting deep level photoemission for thermal emission, and as such can detect states from the valence band up to ~Ec–0.6 eV at 300 K, as described elsewhere [19], [20], [21], [22]. These deeper levels are expected to be important for dictating more persistent degradation phenomenon, such as shifts in static Rd. The deep levels detected in the Vendor 1 HEMTs via drain-controlled ClD-DLOS have activation energies Ec–1.3 eV, Ec–1.7 eV, Ec–1.9 eV and Ec–3.76 eV [19], [20], [21]. [22]. The combined concentration of these deep traps is low before stressing at 1.2x10^{12} cm^{-2} and after stressing increases to 3.2x10^{12} cm^{-2}. However, the total concentration of all ClD-DLOS-detected levels is still less than the concentration of the Ec–0.57 eV traps both before and after ALT. For this reason we consider the Ec–0.57 eV trap to be the dominant RF degradation pathway in these HEMTs while noting that it is also important to comprehensively track deep traps in the entire III-N bandgap for a complete understanding of the degradation effects in GaN HEMTs. In Chapter 5 we will discuss examples where the changes in deep trap concentration induced by the RF stressing far exceed the effects of the Ec–0.57 eV and other thermally detected states.
3.10 Summary and Conclusions

In this chapter a discussion of drain-controlled trap spectroscopy results on three MOCVD-grown HEMTs supplied by two separate commercial sources was provided with a focus on the dominant trap at Ec–0.57 eV located within the drain access region. The increase in the concentration of this trap correlates clearly with RF output power degradation in these HEMTs through increased drain-lag effects. The prevalence of this Ec–0.57 eV trap in the MOCVD HEMTs tested, its sensitivity to ALT, and its correlation with P_{out} reduction through drain lag after stressing indicates that this level is a significant source of degradation and reduced reliability in MOCVD-grown AlGaN/GaN HEMTs.

3.11 References

Chapter 4

Towards a physical understanding of the reliability-limiting $E_C-0.57$ eV trap in GaN HEMTs

4.1 Introduction

In Chapter 2 we described the existence of an $E_C-0.57$ eV trap in a commercial MOCVD grown GaN HEMTs. This same $E_C-0.57$ eV trap has been detected in several other HEMTs from both university and industry sources and also by multiple groups using current-based thermal transient measurements [1] and transconductance frequency dispersion measurements [2]. The $E_C-0.57$ eV trap has been detected both N-polar [3] and Ga-polar HEMTs [4]–[7]. Sozza and co-workers [2] detected an $E_C-0.55$ eV trap in MOCVD AlGaN/GaN HEMTs using transconductance frequency dispersion techniques which is very similar in energy to the $E_C-0.57$ eV defect detected by the OSU team in MOCVD GaN HEMTs. The reports on AlGaN/GaN HEMTs from multiple industry and university sources, all display this $E_C-0.57$ eV drain access region trap as dominant or present to a significant degree, with direct connection to RF output power degradation, drain-lag, current collapse, as a function of prolonged electrical stressing [4]–[7].
This commonplace nature of the Ec−0.57 eV trap has inspired focused efforts to make a more definitive identification of the location of the defect responsible for this trap, with an ultimate goal of identifying its actual source. The drain-controlled ClD-DLTS method has been used to quantitatively determine the energy, capture cross section, and concentration of this trap in numerous HEMTs across several groups and vendors [4]–[7]. This technique has also revealed that the physical location of this trap is within the drain access region of the HEMT, and that it manifests within the lateral field of the virtual gate that extends from the gate toward the drain contact [4]–[7]. However, while ClD-DLTS can distinguish between traps that are physically located in the drain access region versus beneath the gate [3]–[9] the field distribution during the measurement is such that discrimination of barrier versus buffer traps is more complex. As a result, there is current controversy on the issue of which layer the Ec−0.57 eV trap resides. Joh et al. claimed the location of the Ec-0.57 eV to be either in the AlGaN bulk or in the AlGaN surface [1], [10]. Sin et al. [11] and Chini et al. [12] detected an electron trap with activation energy ~0.5 eV trap using conventional drain-current I-DLTS also tentatively assigned its physical location to the AlGaN barrier. Sozza et al. [2] observed that on-state stress leads to greater formation of this trap and linked its formation to hot electron effects happening in the gate-to-drain surface region during the stress. Over the years, the tentative placement of this Ec-0.57 eV trap in the AlGaN-barrier, has led researchers to prematurely assume this trap in the barrier for purposes of simulation studies to model knee-walkout effects [14] and gate-leakage in transistors [15]. It is clear that this trap is of great interest both to the academic research community and to the
industry. For this reason, learning as much about its physical location and its origin is highly desired.

Given the almost ubiquitous occurrence of the Ec-0.57 eV trap and its real measured impact on GaN HEMTs, the controversy regarding Ec–0.57 eV trap location must be first resolved to ultimately identify, and remove or mitigate its physical source. To that end, this work examines the Ec–0.57 eV trap using a set of GaN HEMTs and test structures designed to discriminate barrier from bulk regions as the source. Specifically, we focus on 3 sample sets with 3 measurement methods, namely drain controlled CId-DLTS, conventional capacitance-based deep level transient spectroscopy (DLTS) and nano-DLTS methods [16], [17] applied respectively to the following sample sets: (i) MOCVD-grown AlGaN/GaN compared against InAlN/GaN HEMTs to focus on the impact of barrier material on the Ec–0.57 eV trap; (ii) MOCVD-grown GaN buffers without the presence of any barrier material; and (iii) MOCVD-grown AlGaN/GaN HEMTs which are probed using both CId-DLTS and also nano-DLTS methods that is performed over both the AlGaN surface of the AlGaN/GaN HEMT and also over regions of the same device where the AlGaN has been etched away and the GaN buffer is exposed. These results are ultimately compared to a wealth of prior findings in order to create a consensus of data that targets the real location of this commonly occurring, reliability-limiting defect level in the GaN HEMTs. In the course of this chapter, we will see that its physical location is actually in the GaN buffer and not in the AlGaN barrier as previously thought.
Fig. 4.1 Schematic cross-section of (a) the AlGaN/GaN and (b) the InAlN/GaN HEMTs to physically locate the $E_C-0.57$ eV trap. Both structures were grown using MOCVD on a 4H-SiC substrate and had rectangular gate geometries with silicon nitride passivation in the access regions.
4.2 Impact of different barrier materials on $E_C - 0.57$ eV trap

The schematic illustrations of the AlGaN/GaN and InAlN/GaN HEMTs discussed here are shown in Fig. 4.1. The AlGaN/GaN structure was grown on a 2” SiC substrate using metal organic chemical vapor deposition (MOCVD). The AlGaN/GaN HEMTs are 2 gate-finger devices (each 75 µm wide) with vertical sidewall geometry with gate length $L_G = 0.7 \mu$m and total gate periphery $W_G = 150 \mu$m. The gate-to-source and gate-to-drain spacing of these HEMTs were, respectively, 0.5 µm and 2 µm. The access regions of these AlGaN/GaN HEMTs were passivated using SiNx deposited using plasma enhanced chemical vapor deposition (PECVD). Room temperature Hall effect measurements revealed a two dimensional electron gas (2DEG) charge $n_s = 1.3 \times 10^{13}$ cm$^{-2}$ and mobility of $\mu_n = 1645$ cm$^2$V$^{-1}$s$^{-1}$. The AlGaN/GaN HEMT had a pinch-off voltage $V_P = -4.8$ V and a maximum DC drain-current of ~1.1 A/mm.

The InAlN/GaN HEMT was also grown on SiC substrate using MOCVD. The InAlN film was grown nominally lattice matched to the underlying GaN layer. These HEMTs had 2 finger vertical sidewall Schottky gates (each 100 µm wide) with $L_G = 1 \mu$m and $W_G = 200 \mu$m. The gate-to-source and gate-to-drain spacing of these HEMTs were 1 µm and 2 µm, respectively. The InAlN/GaN HEMTs were passivated in the access regions using PECVD SiNx. A 2DEG density $n_s = 1.5 \times 10^{13}$ cm$^{-2}$ and 2DEG mobility $\mu_n$ of 1300 cm$^2$/Vs were extracted using a combination of CV measurements and contactless eddy current based resistance measurements. The InAlN/GaN HEMT had a $V_P = -4.1$ V, and $I_{DS,\text{max}} \sim 1.2$ A/mm. Despite coming from different sources, the AlGaN/GaN HEMT and the InAlN/GaN HEMT had similar rectangular gate geometries, grown by MOCVD on
SiC substrate, making this a reasonable set of samples to be fairly compared. Detailed description of these structures are in [7].

The drain controlled Cl_D-DLTS methods are designed to extract information about drain access region traps through time-transient measurement of change of parasitic resistance of the transistor switched into its linear regime of operation from a high off-sate $V_{DS}$ [3]–[9]. In both the InAlN/GaN and AlGaN/GaN HEMTs, a constant drain current $I_{DS}$ of ~0.1 A/mm was maintained during the linear regime measurement through dynamic control of the transistor drain-to-source voltage, $V_{DS}$. The drain resistance transient measurement was preceded by a ‘fill-pulse’ where the transistor is switched into pinch off with $V_{GS} = –5 \text{ V}<V_P$ and the off-state $V_{DS} = 10 \text{ V}$ for a fill pulse duration of 100 ms so as to promote virtual gate trapping in the drain-access regions of the HEMT. In the drain-controlled Cl_D-DLTS, such ‘drain-lag’ resistance transients are recorded and averaged from 80 to 400 K in 0.1 K steps. Using double boxcar analytic methods applied to such transients, the trap emission rate can be determined as a function of sample temperature, which allows Arrhenius analysis to determine trap energies and thermal capture crossections. The concentration of each deep level is extracted from the amplitude of the Cl_D-DLTS peak using Eqn 2.1. More details of the experiment are in [7]. Detailed description of drain-controlled Cl_D-DLTS and models are in Chapter 2.
Fig. 4.2 Drain-controlled CI Δ-DLTS of the InAlN/GaN and AlGaN/GaN HEMTs shown in Fig. 1 showing the presence of the same $E_C - 0.57$ eV defect in the samples irrespective of changes in the barrier film composition and/or co-axial strain. This result suggests the $E_C - 0.57$ eV level is not in the barrier layer or at the dielectric/barrier layer interface since the barriers are different materials thus implying that the $E_C - 0.57$ eV level is likely in the GaN buffer.

Fig. 4.3 Arrhenius data of the $E_C - 0.57$ eV from InAlN HEMTs shows excellent overlap with data from AlGaN-barrier HEMTs indicating that all these HEMTs have a common defect causing this signature in the III-N bandgap.
The drain-controlled CDo-DLTS results at 80 s\(^{-1}\) rate window for the InAlN/GaN HEMT and the AlGaN/GaN HEMT are shown in Fig. 4.2. The same dominant negative peaks at \(\sim\)310 K represents the same electron trap in both the HEMTs. The activation energy and thermal capture cross-sections of the trap features were extracted from the Arrhenius plot shown in Fig. 4.3. The overlapping of Arrhenius data over a wide temperature range suggests that the same \(E_C\sim0.57\) eV drain access region trap signature occurs in both types of devices. It seems this \(E_C\sim0.57\) eV level has dominated overall trap spectra measured in both kinds of transistors irrespective of the barrier material or differences in co-axial strain.

The \(\Delta R_D\) peak values extracted from Fig. 4.2 were used in Eqn. (2.1) to extract the concentration of the \(E_C\sim0.57\) eV trap in both the InAlN/GaN and AlGaN/GaN HEMTs to be \(\sim7\times10^{12}\) cm\(^{-2}\) and \(\sim8\times10^{12}\) cm\(^{-2}\). The appearance of the same \(E_C\sim0.57\) eV trap signature with similar \(\Delta R_D\) amplitude and extracted trap concentration directly suggests that the defect source for this trap is independent of the barrier material and/or the degree of co-axial strain present in the barrier layer. This observation is in apparent contrast to what has been noted with various degrees of confidence in previous reports, which also points out the difficulty in making such assignments [1], [10]–[15]. It is also unlikely given that these HEMTs have different SiNx passivation/barrier interfaces in their respective access regions that this trap originates as an interface or surface state and by corollary is strongly suggestive of the GaN buffer. More support to this idea comes from the nano-DLTS experiments and results which is discussed next.
4.3 Nano-DLTS investigation of the $E_C - 0.57$ eV trap location

The AlGaN/GaN HEMTs for the nano-DLTS measurements were Ga-polar devices grown on SiC substrate using MOCVD. The devices had $2 \times 75$ µm wide rectangular gates, and gate-to-source, gate, and gate-to-drain lengths of 0.5 µm, 0.5 to 1 µm and 1 to 6 µm. The HEMTs were processed with ~5 nm of MOCVD silicon nitride passivation in the access regions. More details about this structure are in [15].

The nano-DLTS method is a modified version of scanning Kelvin probe microscopy technique. In this method, nm-scale atomic force microscopy (AFM) is adapted to sense local surface potential changes over semiconductor device surfaces, enabling nanometer-scale spatial resolution and detection of specific defect species in the materials. Figure 4.4 shows the application of this technique to an operational AlGaN/GaN HEMT device. The $V_{GS}$ and $V_{DS}$ biasing of the HEMT was applied using a dual-channel function generator as shown. The surface potential $V_{sp}$ transient was recorded as the tip bias required to minimize the AFM cantilever oscillations at the frequency of the AC signal applied to the AFM tip scanning over the device under test. This technique has already been successfully applied successfully to measure charge near the gate edge of AlGaN/GaN HEMTs [16]. A plan view of the high resolution nanometer-scale nano-DLTS probing is shown in Fig. 4.5(a).
Fig. 4.4: Experimental setup for the nano-DLTS measurement. The gate and drain are biased to $V_{GS}$ and $V_{DS}$, respectively, using a dual-channel function generator. The $V_{sp}$, applied to minimize the attractive electrostatic force between tip and sample, is recorded as the local surface potential. Analysis of $V_{sp}$ transients recorded for different temperatures produce the nano-DLTS results.

Fig. 4.5: (a) Plan view and (b) cross-sectional view of the nano-DLTS study of the AlGaN/GaN HEMT used to identify the location of the $E_c-0.57$ eV trap. Figure 4.3(b) illustrates that the AFM probe tip is not sensitive to traps under the 2DEG in the GaN buffer because of electrostatic screening from the 2DEG at ground potential. However off-the edge of the device, over the exposed GaN surface, the SKPM measurement is sensitive only to GaN buffer traps. Results of these methods are shown in Fig. 4.4.
The AFM tip scans over the exposed AlGaN and GaN surfaces in the drain access regions while the device is simultaneously using the ClD-DLTS biasing conditions that originally revealed the \( E_{C} - 0.57 \) eV trap. Custom designed electronics and feedback techniques were used to optimize the time-response of the \( V_{sp} \) detection circuit allowing accurate surface potential \( V_{sp} \) measurements within ~3 ms of the gate and drain pulses [16], [17]. In order to preferentially focus on the \( E_{C} - 0.57 \) eV trap, in this work, the surface potential transients were recorded between 4 and 125 ms. The \( E_{C} - 0.57 \) eV is thermally active over these time scales over the temperature range of 25 and 52 \( ^\circ \)C used here. The temperature chuck is then held at three different baseplate temperatures of 25, 35 and 52 \( ^\circ \)C after switching the HEMT from \( V_{GS} = -4 \) V <\( V_{T} \) and off-state \( V_{DS} = 10 \) V. Because this technique measures the local surface potential, it is insensitive to traps located below the 2DEG in the GaN buffer as shown in Fig. 4.5(b). This is because all the signal from these traps under the 2DEG are screened from the AFM probe tip by the presence of the 2DEG which is grounded during the measurement. In contrast, however, this method should be sensitive to traps in GaN when the tip is over the exposed GaN region where the AlGaN and the screening effect of the 2DEG ceases to exist. This also is illustrated in Fig. 4.5(b). More details of these SKPM techniques are in [16], [17].
Fig. 4.6 (a) Plan view nano-DLTS map of the access region of the MOCVD-grown AlGaN/GaN HEMT [in the area roughly defined in Fig. 4.3(a)] obtained by pulsing the device similarly to the drain-controlled CID-DLTS measurements. The change in surface potential from 4 to 125 ms is shown in the figure. Nothing but noise was detected over the AlGaN-barrier film under these conditions suggesting that this defect does not occur in the barrier. A larger surface potential signal (seen as lighter shade) corresponding to the $E_C-0.57$ eV trap was detected over the exposed GaN film indicating the $E_C-0.57$ eV level is GaN buffer related and not AlGaN barrier related. (b) Arrhenius overlap of nano-DLTS and CID-DLTS results, suggest that the same $E_C-0.57$ eV trap signature is detected in both measurements.
The nano-DLTS methods described above are now applied specifically to physically locate the $E_c-0.57$ eV level in the AlGaN/GaN system. Under voltage pulsing conditions that mimic the CI-DLTS measurements described previously the surface potential transients due to thermal emission from traps were measured over the AlGaN surface and the exposed GaN. As seen in Fig. 4.6(a) for measurements over the AlGaN surface, $|\Delta V_{sp}|$ does not exceed 6 mV and appears to be dominated by noise and no signature of the $E_c-0.57$ eV trap was detected. The negligible surface potential transient amplitudes over the AlGaN surface was strongly suggestive of the $E_c-0.57$ eV occurring in the GaN buffer because, if that were true, the SKPM technique would be insensitive to that trap located under the 2DEG. In sharp contrast, when the SKPM probe tip was located over the exposed GaN where the AlGaN barrier material had been removed, a strong surface potential transient ($\sim100x$ larger than over the AlGaN surface) became the dominant feature. In this case, there was no 2DEG present to screen the effect of the GaN buffer traps responsible for this large $V_{sp}$ signal. As shown in Fig. 4.6(b), the Arrhenius analysis of the time constants of the SKPM transients (over different temperatures) show excellent agreement with the Arrhenius data of the $E_c-0.57$ eV trap detected from the CI-DLTS measurements, suggesting that this trap does reside in the GaN buffer. Having more or less ruled out the barrier it was only logical to investigate the $E_c-0.57$ eV trap in a simple GaN bulk Schottky device as described next.
4.4 Detection of the $E_C-0.57$ eV trap in bulk GaN

The bulk GaN samples were grown by MOCVD on standard Lumilog STN templates. A highly n-type doped lateral conductive layer was grown 0.5 µm thick followed by 0.5 µm thick active layer doped with Si. These samples were processed with Cl$_2$-based reactive ion etching to etch mesa structures with Ti/Al/Ni/Au Ohmic contacts deposited on the exposed lateral conduction layer and the Ni Schottky contacts deposited on the top active n-GaN layer. All metals were deposited by electron beam deposition and no annealing was performed.

The DLTS trap characterization measurements of these devices were carried out in a temperature controlled stage with a Boonton 7200 capacitance meter, arbitrary waveform generator, and custom software. A quiescent bias of -0.5 V and a filling bias of 0 V were used for the DLTS measurement. The full capacitance transients over a range of 77 to 400 K are recorded digitally and analyzed using box-car method. More details of the DLTS technique and box-car analysis are in Chapter 2.
Fig. 4.7: Comparison of normalized DLTS spectra from the bulk GaN sample and the CI-DLTS spectra from the InAlN/GaN HEMTs and AlGaN/GaN HEMTs for rate window 80 s\(^{-1}\). The presence of the same peak at \(~312\) K across all three samples signifies the presence of the same defect species in all these cases. The energy of this electronic defect was extracted to be \(E_c-0.57\) eV using Arrhenius analysis (see Fig. 4.8) confirming that this level is indeed a GaN buffer defect.

Fig. 4.8: Compilation of Arrhenius data of traps detected using capacitance based DLTS on bulk GaN film grown using MOCVD is compared against that of the \(E_c-0.57\) eV trap detected in MOCVD GaN HEMTs. DLTS on bulk GaN almost always reveals a \(E_c-0.6\) eV trap (among other levels) whose Arrhenius plot matches (in activation energy and capture cross-section \(~5\times10^{-15}\) cm\(^2\)) with that of the \(E_c-0.57\) eV trap in GaN HEMTs thereby strongly agreeing with the existing pieces of evidence that this defect lies within the GaN buffer layer.
The DLTS trap spectra (Fig. 4.7) shows two clear peaks characteristic of an $E_C-0.25$ eV and $E_C-0.6$ eV electron traps. Of these, the $E_C-0.6$ eV trap showed surprisingly similar characteristics and peaked at nominally the same temperatures that the $E_C-0.57$ eV peak occurs in the AlGaN/GaN and InAlN/GaN HEMTs. Closer analysis of these peaks in Fig. 4.8 for different time rate windows yields the Arrhenius data of the $E_C-0.6$ eV trap that almost exactly matches the Arrhenius data of the $E_C-0.57$ eV trap observed in the AlGaN/GaN HEMTs. It is important to note that not only do the energy levels match but so do the cross sections ($\sim 5\times 10^{-15}$ cm$^2$). It is well known in the DLTS community that totally different defects can have the same activation energies but still can signify different defects unless their capture cross sections match. Since both the activation energy and cross-section values match here for data obtained by different types of measurement spread over different kinds of samples, the likelihood that the $E_C-0.57$ eV trap that causes one of the common pathways for GaN HEMT degradation is located in the GaN buffer is very strong. As an interesting footnote, the $E_C-0.57/06$ eV trap has been widely reported since 1994 in bulk GaN [18]–[22]. Studies of capture kinetics (i.e. looking at the dependence of DLTS peak height on fill pulse time) have shown this state to not behave as a simple isolated point defect, and suggestions regarding point defect-dislocation complexes have been made [21]. While compelling correlations have been made in the past to this level and the presence of Fe [20] and passivation by hydrogen [21], a clear atomic-level model linking the defect to either impurity has still been elusive most likely because of the inherently complex nature of this defect and its long history.
Given the range of discussion involved, the work on the exact physical/chemical signature of this defect is still ongoing.

4.5 Gate leakage as a possible filling mechanism of the \( E_C - 0.57 \) eV GaN trap

We now that the \( E_C - 0.57 \) eV trap is widely detected in MOCVD GaN HEMTs and that is a bulk GaN trap. The traps in the buffer should fill during the off-state high \( V_{DS} \) conditions satisfied during the drain-controlled fill conditions i.e. when \( V_{DS} = V_{DS,P} \) and \( |V_{GS}| > |V_T| \). Under these conditions large electric fields are developed at the edge of the gate terminal closest to the drain terminal and these electric fields could serve as transport mechanism for carriers (electrons) leaking from the gate into the GaN buffer traps.

In order to test this theory drain-controlled CI-D-DLTS study were performed in MOCVD GaN HEMTs with widely different gate-current values. These HEMTs denoted as HEMT D and HEMT E were the low leakage and high leakage HEMTs, respectively, obtained from the same vendor and grown and fabricated nominally identically. The results of these experiments are summarized in Fig. 4.9. HEMT D is the lowest leakage RF GaN HEMT measured by this group to date. It is also the first MOCVD grown GaN HEMT to show no \( E_C - 0.57 \) eV signature. However a nearly identical HEMT with higher leakage shows a significant \( E_C - 0.57 \) eV signal. Therefore clearly the appearance of the \( E_C - 0.57 \) eV signature has a strong correlation with the gate leakage of the HEMT.
Figure 4.9(a) Drain-controlled ClD-DLTS thermal scan for 80 s\(^{-1}\) rate window for HEMTs D and E from commercial vendor with gate leakage values different by ~5 orders of magnitude. The low leakage HEMT showed no sign of the Ec–0.57 eV trap but showed presence of a distinct Ec–0.75 eV trap. The high leakage HEMT showed presence of both the Ec–0.57 eV trap and Ec–0.75 eV trap. (b) Arrhenius data shows the Ec–0.57 eV and Ec–0.75 eV traps detected in both the high and low gate leakage HEMTs.
Figure 4.10 Summary of $E_C-0.57$ eV trap signature vs. gate leakage for multiple MOCVD GaN HEMTs obtained from industry. For low leakage case, the $E_C-0.57$ eV trap remains undetected whereas at high leakage values different $\Delta R_D$ signals are observed for different HEMTs and these differences are due to differences in the $E_C-0.57$ eV trap concentrations.

In order to investigate this connection between gate leakage and $E_C-0.57$ eV trap, data was collected from multiple industry including HEMTs A through E from three industry suppliers and plotted as shown in Fig 4.10. To describe this data we propose a gate-leakage assisted electronic filling model for the virtual gate $E_C-0.57$ eV trap during the OFF-state high $V_{DS}$ fill pulse case. The $E_C-0.57$ eV trap is starved of a filling mechanism in low leakage HEMTs because of which it is not detected. This suggests that high leakage may cause filling and subsequent detection of this trap where the trap signal $\Delta R_D$ strength increases non-linearly as a function of the trap concentration, though more work is underway to understand this mechanism.
4.6 Summary and Conclusions

A comprehensive collection of advanced nano- and macro-scale defect spectroscopy techniques were applied over a wide array of GaN based devices to collect overwhelming evidence linking the presence of a critical degradation limiting Ec–0.57 eV trap in MOCVD GaN HEMTs to the GaN buffer. Armed with this piece of information researches and engineers in university and industry alike are now one step closer to identifying the true origin of this almost ubiquitous defect and developing design, growth, and fabrication strategies to alleviate and/or remove the detrimental impact of this defect on device reliability, life-time, and performance.

4.7 References


Chapter 5

Detection of mid-gap trap induced degradation
mechanisms in RF stressed GaN HEMTs with low gate
leakage using deep level optical spectroscopies

5.1 Introduction

In the previous two chapters (3 and 4) we discussed the impact of the Ec–0.57 eV GaN
buffer trap [1]–[3] on HEMT (dynamic) drain-resistance and its subsequent impact on
device characteristics and RF output power degradation. [4]–[6] While a lot of emphasis
was placed on discussion of the properties and location of this particular trap, it is worth
noting that optical based spectroscopy methods were also performed on these HEMTs and
no systematic increase in deep trap levels seemed to explain the output power degradation
effects seen in those samples. This observation however cannot be generalized to all GaN
HEMTs as we will see in this chapter. There have been few reports in literature directly
linking much deeper traps Ec–Et >1 eV to transistor performance and reliability. This
chapter in conjunction with associated publications [9], [10] reports a series of devices
wherein the Ec–0.57 eV trap or for that matter other thermally detected traps in the upper
bandgap are mostly benign as a function of the electrical stressor and instead very deep traps (mid-gap and lower bandgap states) affect the HEMT electrical properties and subsequently cause RF degradation. We report this alternate HEMT performance degradation mechanism induced by very deep states in RF stressed GaN HEMTs with low gate leakage before any stressing. This series of RF stressed HEMTs showed an increase in static on-resistance which was then unambiguously correlated to activation/formation of to mid-gap states ranging from $E_C-1.6$ to $2.5$ eV in the drain-access region. Little to no sign of the $E_C-0.57$ eV trap was detected in the HEMT pre-stressing and it showed slight formation post-stressing but not enough to warrant the RF output power degradation that was observed. We now present the details of this apparently distinct degradation pathway in low leakage GaN HEMTs mediated by deep traps and detected using optical-based trap spectroscopy methods.[9],[10]

5.2 Sample description and RF stressing results

A series of four S-band RF AlGaN/GaN HEMTs were supplied from a commercial vendor. These HEMTs had 0.4 mm of gate periphery and nominally identical electrical characteristics before application of any stressing. The devices 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. These HEMTs also had very low gate leakage ($\sim10^{-8}$ A/mm), (measured at $V_{GS} < V_T$ and $V_{DS}=10$ V) that was at least 2 orders less than the leakage current reported in the industry GaN HEMTs discussed in the previous chapters. It is worth mentioning that these are the lowest leakage Schottky gate AlGaN/GaN RF power
Fig. 5.1 RF output power, gain and power added efficiency show measurable degradation before and after the RF accelerate life testing experiment.

Fig. 5.2 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.
HEMTs measured to date at OSU. The results from one representative device will be presented in this dissertation because the results on all four HEMTs were identical to each other before and after the RF stressing experiment. 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 RF metrics of the HEMTs are shown in Figures 5.1 and 5.2.

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 figure 5.2 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. Other quantities that showed degradation are, the RF gain by ~1.56 dB, power added efficiency by ~5.64 %, all of which were measured for RF input power of 21 dBm. In the following section we describe the effects of the RF stressing on the transistor DC IV characteristics to investigate the possible reason behind the observed RF degradation effects.
Fig. 5.3 Transfer IV characteristics of the GaN HEMTs measured at $V_{DS} = 10$ V at room temperature. Threshold voltage of the HEMT remained unaffected as a function of the RF stressing.

Fig. 5.4 A permanent increase in on-resistance (by $\sim 0.2 \ \Omega\cdot\text{mm}$) 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.
5.3 Transistor IV before and after the RF life testing

The DC transfer IV characteristic of the HEMTs in this work before and after RF stressing are shown in figures 5.3 and 5.4. No measureable $V_T$ shift was observed in the transfer IV characteristics measured at room temperature with $V_{DS} = 10$ V and plotted (on the log-scale) in figure 5.3. This observation suggests that no change in 2DEG density occurred under the gate which therefore suggests no traps were created under the gate in as a function of the RF stressing. On the other hand, the DC output IV characteristics collected in these 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 $\sim 0.2 \, \Omega\cdot\text{mm}$ in these HEMTs after the RF stressing suggests that drain-access region trap formation/activation is likely occurring as a function of the accelerated life test. The knee-walkout in these HEMTs due to drain access region traps reducing the 2DEG density in the parasitic drain access region (and thereby increasing the HEMT on-resistance) is the most likely cause of the observed output power reduction in these HEMTs.

In light of these observations we next discuss drain-controlled CI\textsubscript{D}-DLTS/DLOS trap spectroscopy on these GaN HEMTs focusing specifically on drain-access region traps. The objective here is to monitor the impact of the RF stressing on these drain access region traps in order to correlate with increased on-resistance and thereby possibly to associate this phenomenon to knee-walkout based degradation that could explain the $\sim 1.2$ dB RF output power drop (in Fig. 5.2).
Fig. 5.5 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 Ec−0.72 eV was detected. No sign of the ubiquitous Ec−0.57 eV was detected pre-stressing. After stressing, slight formation of the Ec−0.57 eV trap (by ~1.5x10^11 cm^-2) was accompanied with an increase in Ec−0.72 eV trap concentration (by ~4x10^11 cm^-2).

Fig. 5.6 Gate leakage of these RF GaN-based HEMTs was the lowest ever measured at OSU. Application of RF-stressing saw a significant (~400x) increase in the gate leakage characteristics. The increase in gate leakage was accompanied with the detection of the Ec−0.57 eV trap in the drain controlled ClD-DLTS spectra (see Fig. 5.5).
5.4 Drain controlled CI\textsubscript{D}-DLTS before and after RF stressing

The drain-controlled CI\textsubscript{D}-DLTS of these HEMTs were performed using a fill pulse of $V_{GS} = -3.9$ V, $V_{DS} = 10$ V, for 100 ms duration. The $V_{DS}$ transients were recorded immediately following the fill pulse to maintain a constant current of 0.175 A/mm for $V_{GS} = 0$ V at different temperatures (ranging from 77 to 430 K in 0.1 K steps).

Before any stressing, surprisingly, no sign of the $E_{C}–0.57$ eV trap was detected in these HEMTs (see Fig. 5.5). The HEMTs did however show the presence of an $E_{C}–0.72$ eV electron trap. The absence of the $E_{C}–0.57$ eV trap signature could be due to the fact that these HEMTs are the lowest gate-leakage RF AlGaN/GaN HEMTs measured at OSU to date (see Fig. 5.6). The $E_{C}–0.57$ eV trap was detected only after RF stressing after which the gate leakage current also showed a measurable increase. A detailed discussion of this possible correlation between gate current and $E_{C}–0.57$ eV trap signal was provided in Chapter 4 of this dissertation.

Apart from the absence of the $E_{C}–0.57$ eV trap and very low gate leakage before stressing, what is striking in this HEMT series is how different the degradation mechanisms are compared to the previous batches of higher leakage HEMTs discussed in Chapters 2 and 3. The drain-controlled CI\textsubscript{D}-DLTS and drain-lag results from these low leakage GaN-based HEMTs are directly compared against the previous batch of high-leakage GaN HEMTs in the next section.
Fig. 5.7 Drain-controlled CI\textsubscript{D}-DLTS results plotted for rate window 80 s\textsuperscript{-1} comparing the low leakage GaN HEMTs from this chapter to that of the high leakage HEMTs described in Chapters 2 and 3. In the higher leakage HEMTs, a large increase in the Ec\textendash0.57 eV trap was observed. In stark contrast, the Ec\textendash0.57 eV trap was hardly detected before stressing and did not show a large increase post-stressing. In summary the upper bandgap states seem mostly unaffected as a function of the RF stressing in these low leakage HEMTs.

Fig. 5.8 Drain lag transient comparison of the low leakage HEMTs discussed in this chapter to the high leakage GaN HEMTs those discussed in earlier chapters. The degradation mechanism in the low leakage HEMTs appears very different from that in the high leakage HEMTs where stress-induced dynamic drain-resistance increase mostly thanks to the Ec\textendash0.57 eV trap formation/activation.
5.5 Direct comparison of impact of RF stressing and degradation on drain-access region traps in low and high leakage GaN HEMTs

Figure 5.7 directly compares the drain-controlled CID-DLTS results from the low leakage GaN HEMTs in this work to the high leakage GaN HEMTs reported in previous chapters. Clearly the CID-DLTS amplitude in the low leakage HEMTs remains mostly unaffected as a function of the RF stressing. However, the high leakage HEMTs reported earlier,[1]-[6] a large increase in the Ec–0.57 eV trap signal (by ~5-6x) was reported in addition to an increase in concentration by ~5x10^{12} cm^{-2}. In the higher leakage HEMTs, the increase in the Ec–0.57 eV trap concentration was then directly linked to an increase in dynamic on-resistance increase (or drain-lag increase) by ~0.47 Ω-mm as shown in Fig. 5.8. As discussed in Chapter 2 the degradation in RF output power was then correlated to this increase in the drain-lag phenomenon.

In contrast, the drain-lag transient in the low leakage GaN HEMTs described in this showed little increase in the drain-lag transient (<0.03 Ohm-mm). These results suggest that the output power degradation happening in these low leakage GaN HEMTs is likely not due to upper bandgap states affecting the dynamic on-resistance.

The other most likely suspect for the cause of output power degradation in these low gate leakage HEMTs are the mid-gap and lower bandgap states that could affect the static on-resistance. These deep traps can be probed using optical trap spectroscopy methods as discussed in the following section.
Fig. 5.9 DC output IV, schematic cross-sections, and energy band diagrams of a GaN HEMT with (right panel) and without (left panel) monochromatic light shining on the device. If the illuminated sample shows a lower on-resistance, it is suggestive of optically assisted electron emission of deep levels in the access regions that causes 2DEG recovery and thereby reduced on-resistance. The photon energy used reveals the relative location of the on-resistance affecting deep trap in the band-gap.
5.6 Lighted IV technique: A simple approach to investigate deep traps affecting transistor on-resistance

In order to investigate deep traps in these HEMTs using optical methods, it is useful to first discuss the principles behind a simple experiment that can directly correlate between transistor terminal characteristics to trap states in the band gap. In this technique the output drain current versus drain voltage characteristics at \( V_{GS} = 0 \) V are first recorded in the dark as shown in Fig. 5.9(a) and the on-resistance of the transistor is extracted from the triode region. This static on-resistance should reflect the state of the 2DEG as shown in Fig. 5.9(c) with all deep electron trap states in the band-gap filled with electrons [see Fig. 5.9(e)].

Next the sample is illuminated with sub-bandgap monochromatic light. The energy of the photons of the sub-bandgap light used is large enough to cause optically assisted electron emission of some states in the bandgap as shown in Fig. 5.9(f). The reduction of negative charge in the system recovers the 2DEG density in the access regions as shown in Fig. 5.9(d). This increase in 2DEG density increases the parasitic channel conductivity and thereby reduces the transistor on-resistance. The energy of light used to recover the on-resistance can be used as a measure of the location of the most prominent traps within the band-gap affecting the on-resistance. Such a 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.
Fig. 5.10 DC output IV results of the GaN HEMT before and after stress (a) in the dark, (b) with 1.2 eV, and (c) with 3 eV monochromatic light shining on the GaN HEMT. Figure 5.9(d) summarizes the data collected from these different cases for the HEMTs before and after the RF stress. Data clearly reveals the role of deep traps in these HEMTs.
5.7 Lighted IV results on the low leakage GaN HEMTs

The DC IV characteristics of the GaN HEMTs in question before and after the RF stressing are recorded in the dark and with 1.2 eV and 3 eV of monochromatic light shining. Figure 5.10(a) shows the triode regime of output IV characteristics of the HEMT before and after RF stressing. As was described in Section 5.3 using Fig. 5.4, the stressed HEMT shows a larger on-resistance in comparison to the RF stressed HEMT.

Shining 1.2 eV light on the HEMT does not appear to recover this on-resistance difference between the unstressed and RF stressed HEMTs [see Figs. 5.10(b) and (d)]. This result suggests that the deep traps up to 1.2 eV energy from the conduction band edge seem to have no influence over the steady state on-resistance of the HEMT.

Shining 3 eV energy light on the HEMT almost equalizes the on-resistance of the HEMT before and after the RF stressing [see Figs. 5.10(c) and 5.10(d)]. This result suggests that very deep electron traps within 3 eV of the conduction band edge can fully describe the on-resistance differences before and after the RF stressing experiment on these low leakage GaN HEMTs.

A more high-resolution and thorough identification of these deep levels is achieved through application of the constant drain-controlled CID-DLOS [11] experiment (described earlier in Chapter 2) whose results on this sample series before and after the RF stressing is described next.
Fig. 5.11 Drain-controlled C1D-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 2.5 eV show the most increase and are directly responsible for the static on-resistance increase which likely contributes to the RF output power degradation.

Fig. 5.12 The persistent change in the on-resistance induced by deep traps is ~9x greater than that induced by the upper bandgap states on the dynamic on-resistance. The RF output power degradation in this set of low leakage GaN HEMTs shows a distinct degradation pathway previously not observed in the higher leakage HEMTs where the E_C~0.57 eV trap induced degradation dominated.
5.8 Identification of a different RF degradation mechanism due to persistent drain-resistance increase in the low leakage GaN HEMTs triggered by very deep (Ec–1.6 eV to 2.5 eV) traps

The drain-controlled CIo-DLOS measurement was performed at a constant drain current $I_{DS} = 0.175$ A/mm measured for $V_{GS} = 0$ V as a function of incident photon energy in the range of 1.2 to 4.5 eV. Simply put, the CIo-DLOS measurement monitors the steady state on-resistance of the HEMT as a function of incident photon energy in the low leakage GaN HEMTs before and after the RF stressing. The results of the steady state photoresponse of the transistor on resistance are shown in Fig. 5.11. The negative onsets in the data represent electron trap emission from deep traps and their effect on the transistor on-resistance. The onset energy is an indication of the trap energy referred from the conduction band edge. The biggest increase in the $\Delta R_D$ signal (by $\sim 0.22$ $\Omega$-mm) was observed within a broad energy range of 1.6 and 2.5 eV. This onset suggests formation of mid-gap and lower band-gap traps states after the RF stressing. The increase in on-resistance here matches the increase in static on-resistance increase extracted from the IV characteristics. This match gives us a direct correlation between the mid-gap trap formation and the on-resistance increase observed after the RF stressing. The onset amplitude can be used to extract trap concentrations using relations already discussed in Chapter 2. The corresponding increase in concentration of traps after the RF stressing within this energy range is $\sim 1 \times 10^{12}$ cm$^2$. The chemical/physical identity behind these trap or distribution of traps is currently unknown and has not been reported previously to the best of our
knowledge. That said careful experiments are presently underway to determine the physical origin of these defects.

Figure 5.12 shows that the change in on-resistance produced by the ClD-DLOS deep trap states in the $E_C-1.6$ to $2.5$ eV range is at least $\sim 9x$ larger than that produced by the upper bandgap states detected using the ClD-DLTS. These results go on to show us 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.

In addition to the mid-gap states linked to the on resistance increase, other even deeper electron traps at $E_C-3.25$ eV and $E_C-3.7$ eV were also detected in the GaN HEMT but the $\Delta R_D$ onset of heights and therefore the concentration of these levels ($\sim 0.25 \times 10^{12}$ cm$^{-2}$) remained unaffected after the stressing. The $E_C-3.25$ has been previously reported to be a GaN buffer trap showing a strong correlation with presence of Carbon impurity possibly related to a $C_N$ substitutional defect.[12]-[15] The $E_C-3.7$ eV simply by virtue of its activation energy has to be an AlGaN trap with its origin also likely carbon related according to past reports.[12]

5.9 Summary and Conclusions

In addition to the $E_C-0.57$ eV dynamic on-resistance induced RF degradation mechanism discussed in Chapter 3, a new RF degradation pathway caused by static on-resistance changes in GaN HEMTs was discussed in this chapter and correlated to the formation/activation of mid- and lower bandgap states. In the course of investigation of this new degradation phenomenon, a quick and simple lighted IV technique was developed to correlate the deep traps to on-resistance changes. The work on this sample series serves
as an important reminder that it is essential to continue probe the entire wide-bandgap of
the III-Nitride material system using a combination of optical and thermal means in order
to comprehensively probe for critical reliability limiting defects in the devices. Lastly,
these results once again validate the high fidelity and broad range of applicability of the
CID-DLTS/DLOS suite of methods as a useful tool kit to interrogate reliability problems
in real GaN HEMT devices.
5.10 References


Chapter 6

Deep traps linked to acute degradation of on-resistance in GaN-on-Si power MISHEMTs switched from high voltage conditions

6.1 Introduction

In the chapters 3 through 5 we concerned ourselves exclusively with results from GaN based devices optimized for high frequency and RF applications. However as, GaN HEMTs are also becoming increasingly popular for high voltage power switching applications. While there have been several studies on current collapse and other associated trapping effects in RF GaN HEMTs [1]–[4], there have been limited accounts of trap studies on high voltage GaN-on-Si HEMTs as a function of high voltage switching. Silicon is the substrate of choice for the power industry because of its low cost, large area wafer, and higher thermal conductivity in comparison to sapphire substrates sometimes used as substrates for RF GaN devices [1]–[4]. That being said, there is significant lattice and thermal mismatch between GaN and Si making the III-N epitaxial growth non-trivial and resulting in a large number of defects in the active layers.
These defects when electrically active can impact HEMT performance drastically. There have been limited fundamental exploratory studies on traps throughout the bandgap of GaN-on-Si material let alone in a HEMT configuration. What makes this problem even more exotic is the application of very high electric fields thanks to the very large off-state voltages applied (as high as 600 V). Such high voltages and associated high electric fields previously uncommon in commercial RF GaN HEMTs are common place in these GaN-on-Si power HEMTs. The high fields applied to the edge of the gate or field plate of these devices can potentially induce very severe trapping effects one of which, namely dynamic on-resistance degradation will be presented during the course of this chapter. MISHEMTs and simple AlGaN/GaN Schottky heterostructures from an industry partner were probed using advanced defect spectroscopy tools on a macro and nano-scale. While the MISHEMTs were studied using high voltage C\textsubscript{1D}-DLTS/DLOS [10]–[15], the heterostructure Schottky diodes were investigated using constant capacitance-DLTS/DLOS [16], [17], and nano-DLOS [18], [19]. From this wide assortment of advanced test structures and measurement techniques a series of key observations were made:

- A deep 2 eV trap was directly linked to on-resistance degradation in the MISHEMTs
- Having observed the same trap in the heterostructure Schottky diode (without any dielectric), its physical source was unambiguously confirmed to be \textit{unrelated} to the dielectric/AlGaN interface
Nano-DLOS results and literature review on AlGaN bulk suggest that the trap is not present in the AlGaN bulk layer or AlGaN surface.

Simple bulk concentration arguments for the $E_C - 2$ eV trap that almost pinches off the 2DEG, coupled with trap results from carbon doped bulk GaN in the past suggest that this defect most likely occurs in the GaN buffer.

The following sections describe in detail the sequence of experiments and discussions related to these experiments.

### 6.2 Sample description

The devices described in this study operate in depletion mode and were received from an industry partner. These devices consist of an under-gate dielectric, making them GaN based metal-insulator-semiconductor HEMTs (MISHEMTs). These structures were grown and fabricated on 6-inch Si (111) wafers. The MISHEMTs were outfitted with multiple field-plates, the dimensions of which were optimized to achieve a breakdown voltage in excess of 600 V. The maximum drain current at $V_{GS} = 0$ V was $\sim 0.45$ A/mm. Because these devices represent a relatively early generation of power switching HEMTs from the industry partner, the steady-state on-resistance $R_{ON}$ of these devices is between 20 and 30 $\Omega$-mm which is about $\sim 2-3x$ higher than that typically reported in literature [2], [3]. This higher steady-state $R_{ON}$ should not however affect the trap induced dynamic $R_{ON}$ effects or the general conclusions from this work. Hall measurements were performed on Vander Pauw structures to extract a 2DEG density of $1 \times 10^{13}$ cm$^{-2}$ and a Hall mobility of 1900 cm$^2$/Vs/ In addition to Hall measurements, four point probe IV
measurements on the Vander Pauw structure were also used to extract the drift mobility of these devices at room temperature which was measured to be \( \sim 1804 \text{ cm}^2/\text{Vs} \).

### 6.3 Definition of dynamic on-resistance

A critical requirement of GaN HEMTs, especially those optimized for high voltage switching applications, is a very low on-resistance \( R_{\text{ON}} \) immediately (within \( \mu \text{s} \)) of switching the transistor from a high off-state \( V_{\text{DS}} \) case to a low \( V_{\text{DS}} \) triode case [1]–[4], [20], [21]. Figs. 6.1 and 6.2 illustrate a severe version of this problem on GaN HEMTs switched from high-\( V_{\text{DS}} \) off state to a low voltage condition. The original output IV characteristics of the transistor are severely degraded because of the large on-resistance induced by the high voltage switching. Fig. 6.2 shows that the transistor slowly recovers in the dark from this high resistance case as a function of time. As is clear this phenomenon is highly undesirable in transistors designed for high voltage switching applications. We apply our advanced and direct trap spectroscopy CID-DLTS/DLOS tool kit on these high voltage MISHEMTs to understand this phenomenon and delineate the possible role of traps in it.
Fig. 6.1 Illustration of dynamic $R_{ON}$ degradation effect in the output IV characteristics of a GaN HEMT after switching from a high off-state $V_{DS}$ condition. Dynamic $R_{ON}$ (measured at short times) is clearly distinct and much larger than steady state $R_{ON}$ measured long after the off-state pulsing.

Fig. 6.2 Time dependence of on-resistance at 300 K. The transistor on-resistance is very large at short times (shown in red) and recovers as a function of time (shown in green) to steady state values (black).
6.4 Dynamic $R_{ON}$ as a function of different off-state $V_{DS}$

The on-resistance of the MISHEMT in study was monitored soon after a fill pulse from $V_{GS} = -10$ V and different off-state $V_{DS}$. The on-resistance was measured over long times (up to $10^4$ s) by maintaining a constant current $I_{DS} = 0.42$ mA/mm and dynamically controlling the drain-voltage. The change in drain voltage can be directly converted to change in on-resistance. As seen in Fig. 6.3, the on-resistance transient showed no significant increase for off-state $V_{DS}$ voltages up to 150 V. However for drain-voltage exceeding 250 V a very large and persistent on-resistance signal is measured signifying an almost total current collapse in the MISHEMT being measured. Given enough time (in this case $> 3$ hours), the on-resistance recovers back to the original static $R_{ON}$ value the HEMT had before application of the high voltages. Fig. 6.4 shows $R_{ON}$ values recorded for the MISHEMT at $t=1$ s after the fill pulse. A clear onset is observed at off-state $V_{DS} \sim 200$ V. This increase in resistance is not due to $V_T$-shifts because very little $V_T$ change of it ($<100$ mV) was observed in the MISHEMT during the high off-state $V_{DS}$ switching. On the contrary, this large dynamic $R_{ON}$ is consistent with high field-induced electron trapping effects in the drain access region. Based on three terminal capacitance measurements similar to previous reports [2], [20] the drain to gate capacitance was measured with the $V_{GS} < V_T$ versus $V_{DS}$. These results indicated that the peak electric field was at the edge of last field plate for $V_{DS} > 200$ V, which corresponds to the onset in Fig. 6.4 suggesting that the trapping occurs primarily at the edge of the field plate. The $R_{ON}$ recovery as a function of time suggests electron emission where the 2DEG recovers over time.
Fig. 6.3 On-resistance transients recorded for different off-state $V_{DS}$ conditions. Up to 150 V off-state $V_{DS}$, no significant increase in dynamic on-resistance was observed. For off-state $V_{DS}$ cases at and above 250 V very large and persistent $R_{ON}$ was observed which then tended to recover to steady state $R_{ON}$ case at very long times ($> 10^4$ seconds). The increase in on-resistance suggests there is an injection of large negative charge in the system during the high voltage high field switching. This negative charge effectively reduces the 2DEG density and thereby increases the on-resistance of the MISHEMT. The long recovery time hints that the charge states are deep electron traps emitting over time.

Fig. 6.4 On-resistance sampled at 1 s after switching the MISHEMT as discussed in Fig. 6.1 for different off-state drain voltages. A sharp onset at 200 V indicates that significant on-resistance increases take place only after some threshold electric field is exceeded at the edge of the longest field plate where the electron trapping occurs.
6.5 Impact of high off state $V_{DS}$ switching on MISHEMT threshold voltage

The high off-state $V_{DS}$ switching showed much less impact on the transistor $V_T$ compared to the on-resistance. This changes in $V_T$ were limited to within 100 mV and nowhere close to large enough to reproduce the massive current collapse that was being observed in the MISHEMTs (see Fig. 6.5). These results tell us that the impact under the gate for the given switching conditions is minimal in these devices. More work is presently underway to understand the sign of these transients observed, but for now it is safe to ignore these under-gate effects in comparison to the large $R_{ON}$ effect due to severe trapping in the drain access regions on which we will be focusing the rest of this chapter.

![Graph showing threshold voltage transients](image)

Fig. 6.5 Threshold voltage transients of the MISHEMT recorded immediately after switching from off-state high $V_{DS}$ condition to on-state saturation with $V_{DS} = 10$ V at constant drain current of 20 $\mu$A/mm. The $V_T$ shows little dependence (<100 mV change) on the high voltage switching conditions used suggesting that the given switching conditions produce minimal impact under the gate. All the effects on the $R_{ON}$ are entirely due to effects physically limited to the drain access region.
6.6 Isothermal DLTS analysis of the \( R_{\text{ON}} \) time transients

The \( R_{\text{ON}} \) transients were additionally recorded for different baseplate temperatures in order to explore the temperature dependence of the time constants of these transients and to possibly extract activation energies of the traps involved. Figure 6.6 shows this data collected for a given off-state \( V_{\text{DS}} = 250 \, \text{V} \). Interestingly at low temperatures, little \( R_{\text{ON}} \) degradation was observed. But with increasing baseplate temperatures, a larger amplitude \( R_{\text{ON}} \) transient was observed. From a cursory scan, the time-constant of the transient apparently seems unaffected by the base-plate temperature. In order to clearly detect the time-constant of the \( R_{\text{ON}} \) transient, iso-thermal DLTS analysis was performed for each temperature the transient was recorded.

In iso-thermal DLTS was obtained using box-car analysis with times \( t_1 \) and \( t_2 \) defining the edges of the box-car rate window with \( t_2 = 2.5 \times t_1 \). The ratio between \( t_2 \) and \( t_1 \) is defined by a constant \( \beta \) (= 2.5 here). The \( t_1 \) was varied from 2 ms to 4000 s and consequently the \( t_2 \) varied between 5 ms and 10000 s. The iso-thermal DLTS plots were created using the expressions [22], [23]:

\[
\Delta R_{\text{ON}} = \left( \frac{\beta^{\beta(\beta^{-1})}}{\beta - 1} \right)^* [R_{\text{ON}}(t_1) - R_{\text{ON}}(t_2)] \tag{6.1}
\]

\[
\tau = \frac{(t_2 - t_1)}{\ln(t_2 / t_1)} \tag{6.2}
\]

where \( R_{\text{ON}}(t_1) \) and \( R_{\text{ON}}(t_2) \) are the values of on-resistance recorded at times \( t_1 \) and \( t_2 \) respectively. Because the \( R_{\text{ON}}(t_2) < R_{\text{ON}}(t_1) \), the calculated \( \Delta R_{\text{ON}} \) values plotted are negative in sign according to the convention adopted in Eqn 6.1. The first term in Eqn 6.1 that is a function of \( \beta \), arises from the correction factor required to capture the full
amplitude of the $R_{\text{ON}}$ transient assuming it is a pure exponential function. For $\beta = 2.5$ this value comes to $\sim 3.07$.

For a given temperature, the negative peaks in the isothermal DLTS data represents the characteristic time-constant of the transient at that temperature. If this process were truly thermally activated, then change of baseplate temperature could possibly change the characteristic time constant of the $R_{\text{ON}}$ transient being measured. However as is shown in Fig. 6.7(a), the peak positions hardly changed as a function of temperature. A less than $\sim 2x$ change was observed for an increase in 100 K of base plate temperature. The Arrhenius plot extracted from this data is plotted in Fig. 6.7 (b) reveals a thermal activation energy of 0.02 eV and a non-physically small thermal capture cross-section of $1 \times 10^{-28}$ cm$^2$. For example the Arrhenius data of the $E_c-0.57$ eV level which is a typical thermally activated trap and already much discussed in Chapters 3 and 4 is plotted alongside the new data for comparison in Fig. 6.7(b). While the $E_c-0.57$ eV trap have characteristic electron emission time constant vary by at least 3 orders of magnitude over a $\sim 100$ K temperature ranges, the time constant of the dynamic $R_{\text{ON}}$ transient collected in the GaN-on-Si MISHEMT is hardly affected.

All these results allude to the fact that the dynamic $R_{\text{ON}}$ causing defect in the GaN-on-Si MISHEMTs does not exhibit the characteristics of a typical thermally activated trap. Suspecting deeper traps, optical spectroscopy is performed as described in the next section. In a later section, we will revisit the reasons as to why the emission of the traps possibly follows this non-thermally activated trend in these MISHEMT devices.
Fig. 6.6 On-resistance transients recorded for given off-state high \( V_{DS} \) switching conditions at different baseplate temperatures. The amplitude of the on-resistance transient has a strong temperature dependence whereas the time constant seems mostly unaffected. Closer inspection of time-constants for a given temperature is obtained using iso-thermal DLTS analysis of these transients shown in the Fig. 6.7.

![Graph showing on-resistance transients](image)

Fig. 6.7 Iso-thermal DLTS analysis on \( R_{ON} \) transients shown in Fig. 6.6 reveal characteristic time-constant of the respective transients for that given temperature. What is striking here is that the time-constant of the transient features observed is mostly independent of temperature unlike a traditional thermally activated traps detected in past work. This fact is obvious from the Arrhenius plot shown in figure 6.6(b). The extracted thermal activation energy of this process (shown as closed symbols) is 0.02 eV and apparent thermal capture cross-section \( \sim 1 \times 10^{-28} \text{ cm}^2 \) which is non-physical. These results reveal that this phenomenon is not a typically thermally activated trap emission process.
6.7 Directly linking the massive $R_{ON}$ degradation to a deep $E_C-2\,\text{eV}$ trap

As discussed in the previous section, the non-thermally activated process prevents determination of the trap energies using traditional DLTS-based approaches and so to overcome this, the trap energies were determined using optical stimulation (i.e. using ClD-DLOS). The results of ClD-DLOS on the MISHEMT are shown in Fig. 6.8. In the MISHEMT, the $R_{ON}$ after off-state $V_{DS} = 250\,\text{V}$ application is persistently high at $~150\,\Omega\cdot\text{mm}$ and is independent of light with energy $<2\,\text{eV}$. However for light energies $>2\,\text{eV}$, photoionization of a $\sim E_C-2\,\text{eV}$ trap recovers the entire $R_{ON}$. This $\Delta R_{ON}$ amplitude can be used to extract a (sheet) trap density using the expression:

$$
\Delta R_{ON} = \left( n_s \right)^2 \left[ n_s - \frac{L_{dep}}{q \mu_n \Delta R_{ON}} \right]^{-1}
$$

Where $n_s = 1 \times 10^{13}\,\text{cm}^{-2}$ and $\mu_n = 1804\,\text{cm}^2/\text{Vs}$ and $L_{dep}$ is the lateral depletion region over which the high electric field induce the trapping in the $E_C-2\,\text{eV}$ trap. Given the difficulty to analytically model $L_{dep}$ in such a complex structure for such high electric fields, we here instead assume different values of $L_{dep}$ as shown in the Table. 6.1

<table>
<thead>
<tr>
<th>$L_{dep}$ (nm)</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_T$ ($\times 10^{12},\text{cm}^{-2}$)</td>
<td>10.000</td>
<td>9.999</td>
<td>9.997</td>
<td>9.977</td>
<td>9.774</td>
</tr>
</tbody>
</table>

Table 6.1 $E_C-2\,\text{eV}$ trap density estimated for different $L_{dep}$ values

Results in Table 6.1 suggest that a large concentration of traps $n_T \sim n_s$ is required to completely pinch-off of the MISHEMT in the dark [Fig. 6.9 (a)]. Figure 6.9(b) shows optically assisted electron emission from the deep trap by shining light energies $>2\,\text{eV}$. 

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Fig. 6.8 Constant drain current DLOS results from the MISHEMT measured as a function of the high voltage switching. In the dark and at incident photon energies < 2 eV the on-resistance remained persistently high (~150 Ω-mm) soon after switching from off-state $V_{DS} = 250$ V case. The application of light energies > 2 eV recovers the on-resistance to the original steady state values ~ 30 Ω-mm. The sharp negative onset at 2 eV informs us of an $E_C$–2eV electron trap directly linked to this $R_{ON}$ degradation effect.

Fig. 6.9 Schematic cross-sections of the MISHEMT showing the charge state of the $E_C$–2 eV trap (a) soon after high off-state $V_{DS}$ switching (b) after shining light energies > 2 eV. The high voltage induces trapping of electrons in the $E_C$–2 eV trap mostly at the edge of the field plate, thereby causing a reduction of 2DEG charge density and a massive increase in on-resistance. The electrons from the $E_C$–2 eV are emitted using sub-bandgap monochromatic light energies exceeding 2 eV in photon energy. This electron emission results in 2DEG recovery and reduction of on-resistance to steady state values before application of any high off-state $V_{DS}$.
6.8 Exploration of the physical location of the \(E_C-2eV\) trap

With the critical trap energy associated with the \(R_{ON}\) degradation identified and its lateral position localized to the edge of the field plate, determination of its vertical position was the next step. To accomplish this, the AlGaN/GaN Schottky diode structure was measured using CC-DLOS at a small constant capacitance of 8.3 nF/cm\(^2\). The voltage \(V_{\text{Schottky}}\) was dynamically controlled using a feedback control circuit to maintain the constant capacitance. This voltage was then monitored as a function of incident photon energy. This value (and corresponding biasing) was chosen to minimize the response from the thin AlGaN barrier and AlGaN/GaN interface because under this condition a large percent (~98%) of the depletion region is in the GaN buffer layer thereby minimizing the impact of any trapping effects within the AlGaN barrier layer.

As seen in Fig. 6.10, the CC-DLOS results of the AlGaN/GaN Schottky diode exhibits a negative onset at \(~E_C-2\) eV that matches the \(~E_C-2\) eV trap signature detected using CI\(\alpha\)-DLOS in the MISHEMT (shown in the same figure). Furthermore, the CC-DLOS onset at \(E_C-3.28\) eV is characteristic of a well-studied level in n-GaN that has been attributed to residual carbon impurities [24], [25], and serves as a marker that the CC-DLOS spectrum is dominated by levels in the GaN buffer. While the GaN bandedge is visible, there is evidence of a feature related to the AlGaN bandedge or any trap between \(~3.7\) eV – 4eV previously [26], [27] associated with AlGaN levels in CC-DLOS spectra of these test structures. These observations combined with the fact that there is no dielectric layer in these Schottky test structures, suggests that the \(~E_C-2\) eV level resides within the GaN buffer.
Fig. 6.10 Comparison of CC-DLOS results from the AlGaN/GaN Schottky diode to CID-DLOS data from the MISHEMT. Both the HEMT and the diode show the same EC–2eV trap feature which proves that this feature is unrelated to the dielectric in the MISHEMT. Also, the CC-DLOS from the Schottky diode reveal EC–3.28 eV trap, a well-known GaN defect and a GaN bandedge in addition to the EC–2eV trap. The absence of tell-tale AlGaN features in the Schottky diode CC-DLOS spectra suggests that the EC–2eV trap is likely GaN buffer related.
In addition to CC-DLOS, nano-scale trap spectroscopy was performed on the AlGaN/GaN Schottky diodes in an attempt to determine the physical location of the \(~E_c-2\) eV trap. This technique is an atomic force microscopy (AFM) based approach that enables measurements of local surface potential with nm-scale spatial resolution. The nm-scale-time-resolved surface potential transients measured using this method are recorded between the Schottky metal and Ohmic contact of the Schottky diode test structures as shown in Fig. 6.11. The biasing of the Schottky metal (with respect to the Ohmic terminal contacting the 2DEG) was achieved using a function generator. Custom designed electronics and feedback techniques were used to optimize the time response of the measured surface potential transient \(V_{sp}\) [18], [19]. The figure 6.11 shows a cross-sectional view of the AlGaN/GaN test structure over which the local \(V_{sp}\) was recorded. The 2DEG in the HEMT acts as a ground plane during the surface potential measurements. Because of this reason, the nano-DLOS technique is sensitive exclusively to trapped charge in the AlGaN surface or in the AlGaN bulk but is ‘blind’ to traps under the 2DEG [18], [19]. Spectrally resolved sub-bandgap monochromatic light was then used to illuminate the structure in conjunction with a switching scheme identical to the one used for the CC-DLOS measurements described earlier. The objective was to locate whether the 2 eV trap occurred in the AlGaN bulk or surface.
Fig. 6.11 Schematic showing the nano-scale vertical and lateral sensitivity of the AFM probe tip used in the nano-DLOS measurements.

Fig. 6.12 Nano-scale DLOS results sensitive to AlGaN surface potential transients reveal no sign of the $E_C - 2 \text{eV}$ trap despite switching the Schottky diode in the same scheme as the CC-DLOS measurement. An $E_C - 3.7 \text{eV}$ AlGaN trap signature and the AlGaN bandedge were detected in the surface potential spectra underscoring the ability to this technique to monitor traps exclusively in the AlGaN film.
Figure 6.12 shows the steady state surface potential trap signal collected as a function of incident optical energy. Negative onsets represent electron traps in the AlGaN bulk or surface. What was noteworthy was the complete absence of the $E_C-2$ eV trap and all other known GaN related features such as the $E_C-3.28$ eV trap [24], [25] and the GaN bandedge observed in the CC-DLOS data. Instead, the only AlGaN-related features were observed, namely an $E_C-3.7$ eV trap and the AlGaN bandedge ~4 eV. [26], [27] This marked difference in the CC-DLOS and nano-DLOS goes to show the preferential sensitivity of this nano-DLOS methods to the AlGaN film. This piece of data once again suggests that the $E_C-2$ eV trap is very likely present in the GaN buffer and not in the AlGaN barrier.

6.9 Arguments against $E_C-2$ eV occurring in the AlGaN

It was estimated in Table 6.1 that the sheet concentration of the $E_C-2$ eV trap in the MISHEMT had to be on the order of $\sim 1 \times 10^{13}$ cm$^{-2}$ in order to achieve the almost complete pinch-off in the devices soon after the high off-state $V_{DS}$ switching in the dark. This sheet concentration if assumed over ~30 nm AlGaN thickness translates to a bulk concentration $\sim 3.33 \times 10^{18}$ cm$^{-3}$. Such a high trap concentration is very unlikely due to several reasons. Previous reports on DLOS studies in bulk AlGaN have not revealed an $E_C-2$ eV trap. Also the total trap concentration previously reported in bulk AlGaN did not exceed $3 \times 10^{17}$ cm$^{-3}$. It is therefore very unlikely that a single $E_C-2$ eV trap could occur in such high concentrations in the AlGaN film in the MISHEMTs under study.
6.10 Arguments for $E_C - 2\ eV$ occurring in the GaN buffer

Invoking the sheet charge argument again, the approximate bulk density of the 2 eV traps if uniformly distributed over say ~3 $\mu$m of GaN would be $3.33 \times 10^{16} \ cm^{-3}$. This idea finds support from past trap studies on carbon doped GaN grown using MBE. In this past work an $\sim E_C - 2\ eV$ trap was detected in the GaN in concentrations as high as $1.4 \times 10^{16} \ cm^{-3}$ which within striking range of the required trap concentration to achieve complete pinch-off in the MISHEMTs described in this chapter. It is therefore highly reasonable for the $E_C - 2\ eV$ trap causing the massive $R_{ON}$ degradation and current collapse in the MISHEMTs to occur within the GaN buffer.

6.11 Working model describing the $E_C - 2eV$ trap effects in the MISHEMTs

It is now quite clear that the $E_C - 2\ eV$ defect is located in the GaN buffer. Given that it was detected in the Schottky diode test structures were no high voltage electric stressing was applied to have formed this defect in any localized fashion, this trap is likely to be present uniformly under the gate and in the access regions of the buffer regions of the MISHEMT. However, the modulation of these traps is highly localized at the field plate edge because this process is likely triggered by the highly non-uniform electric fields that peak at the field plate edges in the structures during the application of high off state $V_{DS}$ ($>200\ V$). It is therefore the combination of the uniform presence of this pre-existing $E_C - 2\ eV$ trap in large bulk concentrations ($\sim 3 \times 10^{16} \ cm^{-3}$) and the
occurrence of localized peak electric fields at the field plate edges that is responsible for the observed $R_{ON}$ degradation and the related total current collapse in these MISHEMTs.

To better understand how the $E_C-2$ eV GaN buffer defect might explain the observations such as non-thermal trap emission in the MISHEMT and filling and emptying mechanisms in both the Schottky diode and MISHEMT devices, a simple model is proposed. In this model, the position of the Fermi level deep in the semi-insulating GaN buffer is estimated using the knowledge of filling and emptying of the $E_C-2$ eV trap in the MISHEMTs. Under high off-state $V_{DS}$, more negative charge is injected into the system which means that the $E_C-2$ eV trap is filled with electrons. But this would mean that this trap was originally devoid of electrons and by extension was located above the Fermi level deep in the semi-insulating GaN buffer before the application of any high voltage. Armed with the approximate knowledge of the Fermi level position assumption we now present our model for the $E_C-2$ eV buffer trapping in the transistors and the Schottky diodes.

Figure 6.13 represents our proposed model. The energy band diagrams plotted as Figs 6.13(b) and 6.13(c) represent those extracted along a vertical cutline $yy'$ [shown in Fig. 6.13(a)] taken just beyond the longest field plate. Before application of any high voltage in equilibrium condition, the modeled occupancy of the 2 eV trap in the GaN buffer is shown in Fig. 6.13(b). Because we have already assumed that the Fermi level of the buffer is likely to be located at or below the 2 eV trap, only the traps located close to the AlGaN/GaN interface are filled with electrons and therefore ionized. The occurrence of filled $E_C-2$ eV traps before application of any high voltage is validated by the CC-DLOS
Figure 6.13 (a) Schematic cross-section of the HEMT and a vertical cutline yy’ just beyond the longest field plate. The corresponding energy band-diagrams along this cutline are plotted in (b) equilibrium, and (c) in non-equilibrium soon after high off-state $V_{DS}$ application. Assuming the Fermi level is energetically located below the 2 eV trap, only the traps physically close (i.e. few hundred nm) to the AlGaN barrier/GaN buffer interface are filled with electrons during equilibrium. The $E_{C}–2$ eV trap located deeper in the GaN remains unfilled. After application of high voltages and high electric fields at the edge of the field plate, localized electron trapping causes substantial filling of the $E_{C}–2$ eV trap deep in the buffer resulting in a localized pinch-off of the 2DEG in the drain access region and very high on-resistance values.
Figure 6.14 (a) Schematic cross-section of the HEMT and a horizontal cutline xx’ deep in the GaN buffer. The corresponding energy band-diagrams along this cutline are plotted in (b) equilibrium, and (c) in non-equilibrium soon after high off-state $V_{DS}$ application. After application of high voltages and high electric fields at the edge of the field plate, localized electron trapping in the $E_C-2$ eV trap deep in the GaN buffer results in severe localized band bending and almost complete pinch-off of the 2DEG in the drain thereby causing the large $R_{ON}$ degradation. The severely distorted band-diagrams shown in low field non-equilibrium conditions in Fig 10(c) could explain how the $E_C-2$ eV emits electrons as a function of time through an atypical non-thermally activated process.
results. The detection of Ec–2 eV traps in the two terminal Schottky diode structures where no high fields were applied, proves that it is not necessary for high fields to exist to be able detect the Ec–2 eV signature in the Schottky diodes. What was detected in the CC-DLOS measurements is simply the small fraction of the filled or ionized Ec–2 eV traps near the AlGaN/GaN interface that remains filled by virtue of its location below the Fermi level. However in the MISHEMT, for this trap to have a massive impact on the transistor terminal characteristics, it is essential that traps deep in the buffer also participate. Their participation is ensured by the application of high electric field during the high off-state VDS switching.

During the application of high off-state VDS (> 200V), the very high electric fields localized at the edge of the field plates can cause severe localized electron injection in the Ec–2 eV trap deep into the GaN buffer through possible mechanisms such as Zener tunneling, hot carrier injection, reverse gate leakage among several others [20], [21]. With the traps now filled with electrons, the modeled energy band diagrams of the transistor soon after the high voltage fill pulse are as shown in Fig. 6.13(c). The additional negative charge now present in the system causes a severe back-gating effect that almost completely pinches off the 2DEG and causes the large RON effect. The transistor recovers from this state and reverts back to state represented in Fig. 6.13(b) either after long wait times (>3 hrs) or when exposed to light with photon energies > 2 eV. Figure 6.14 shows the energy band-diagrams of the HEMT along a horizontal cutline resonated before and after the high voltage application. Fig. 6.14(a) shows that the cutline is obtained in deep the GaN buffer. In equilibrium conditions shown in Fig. 6.14(b), the
Ec–2 eV trap remains free of electrons because it lies above the Fermi level this deep in the GaN buffer. In Fig. 6.14(c), the non-equilibrium energy band diagrams soon after the application of high voltage are shown. The peak electric fields occurring at the edge of the field plate caused localized electron trapping only at the edge of the field plate. This massive electron trapping causing the severe band bending that prevent lateral conduction of electron from the source to the drain thereby increasing the $R_{ON}$ manifold. As mentioned earlier, waiting for long times recovers the transistor to its original state. This is possible because of discharging of the Ec–2 eV trap through a non-thermally assisted process akin to a tunneling mechanism. The shape of this band diagrams shown in Fig. 6.14(c) soon after the high voltage off-state fill pulse provides an explanation for how such very deep Ec–2 eV traps can recover within a few hours when a traditional thermal detrapping process from such a deep level would have typically taken several decades. This is one possible explanation of the non-thermal emission of the Ec–2eV trap observed using the iso-thermal DLTS measurements.

**6.12 Summary and Conclusions**

In conclusion, spatially sensitive optical and thermal trap spectroscopies were applied to GaN/Si MISHEMTs. A deep ~Ec–2 eV electron trap was shown to be responsible for the observed $R_{ON}$ degradation of the device that occurs soon after high voltage (>200V) switching. This trap is activated at the edge of the field plate on application of high voltages (>200V) and shows characteristics similar to that of previously detected virtual-gate traps [12]–[15]. Detailed comparison with AlGaN/GaN Schottky diodes suggests that this trap is located within the GaN buffer, and does not
appear to be related to the AlGaN barrier or surface states. The severe $R_{\text{ON}}$ degradation phenomenon, which is a pressing problem in these MISHEMT devices, may be greatly used through a combination of (a) judicious epitaxial growth and design strategies targeted to mitigate the concentrations of electrically active defects in the MISHEMT (especially in the buffer and (b) field management practices including but not limited to enhanced field plate design strategies and optical control of 2DEG density to reduce fields without compromising performance.

### 6.13 References


Chapter 7

Proton irradiation-induced traps causing $V_T$ instabilities in AlGaN/GaN HEMTs

7.1 Introduction

In the chapters preceding this one, all the GaN HEMTs studied were subjected to different variations of electrical stressing (either DC or RF) sometimes in conjunction with high baseplate temperatures. In this chapter we explore effects of high energy particle irradiation of HEMTs targeted for extra-terrestrial applications. While it is conventional wisdom that wide-bandgap semiconductors such as GaN are very radiation hard compared to GaAs and other III-V systems [1]–[3], HEMT devices have in most occasions shown degradation in terminal IV characteristics typically attributed to displacement damage [4]–[5]. Experiments by different groups revealed that using higher energies of proton irradiation produces less damage than using low energy irradiation of $\sim 2$ MeV [6]–[8]. While many of these earlier reports have reported these degradation effects, there has been sparse reports linking the observed IV degradation to a specific traps [9]. In this work we utilize the high resolution constant current trap spectroscopy
methods to directly correlate specific defects to a given degradation mechanism. In the
given series of AlGaN/GaN HEMTs and AlGaN/GaN Schottky diodes were subjected to
1.8 MeV of proton irradiation and two distinct degradation components were identified,
namely [11]–[12]:

a) A static (or steady state) positive shift in $V_T$ by $\sim 0.59$ V

b) An increase in the dynamic (bias and time dependent) $V_T$ by $\sim 0.1$ V

The first and largest effect will be shown to be linked to very deep traps (at 1.3 eV
and 3.25 eV from the conduction band edge) occurring in the GaN buffer. Evidence for
this comes from earlier proton irradiation work [13] in bulk GaN in combination with
Atlas Silvaco based simulations in this work [11]–[12]. The second effect was shown to
be linked entirely to the irradiation induced formation of an $E_C-0.72$ eV GaN buffer trap
using CID-DLTS methods in combination with carefully designed pulsed IV
measurements. The following sections describe the details of the proton irradiation and
trap characterization experiments.

### 7.2 Sample information about the AlGaN/GaN HEMTs

A series of X-band RF AlGaN/GaN HEMTs were supplied from a commercial
vendor. These HEMTs had 0.4 mm of gate periphery and nominally identical electrical
characteristics before application of any radiation. The HEMTs were passivated using
SiNx in the ungated/access region. These devices had a $I_{DS,max}$ of 0.75 A/mm at $V_{GS} = 0$ V
and a $V_T$ of $-2.5$ V measured at $V_{DS} = 2$ V. The HEMTs had gate leakage of $\sim 6 \times 10^{-7}$
A/mm, measured at $V_{GS} < V_T$ and $V_{DS} = 10$ V (high enough to ‘see’ the $E_C-0.57$ eV trap).
The HEMTs were mounted and measured on a 64-pin ceramic pin grid array package.
7.3 Radiation experiment and RF degradation

The packaged HEMTs were irradiated at using protons at 1.8 MeV at Vanderbilt University using a National Electronics Corporation Pelletron accelerator (Model #5SDH-4). All pins of package holding the HEMT were grounded during the irradiation experiment. The RF small signal gain of the HEMT was recorded as a function of different radiation doses as shown in Fig. 7.1. A reduction in RF gain by ~ 1.2 dB was detected at the highest proton dose of $1 \times 10^{14}$ cm$^{-2}$. What this result tells us is that using the $1 \times 10^{14}$ cm$^{-2}$ of 1.8 MeV protons, a very measureable and significant failure in GaN HEMT performance was observed. In the following section we explore possible mechanisms behind the observed degradation of RF performance and the specific role of traps in this phenomenon.

![Fig. 7.1 RF small signal gain decreases as a function of increasing proton fluence. At the highest proton fluence of $1 \times 10^{14}$ cm$^{-2}$ a 1.2 dB drop in gain is observed, large enough to be classified as device failure.](image)
Fig. 7.2 DC output IV characteristics of the GaN HEMT measured before and after a dose of 1.8 MeV protons at a fluence of $1 \times 10^{14}$ cm$^{-2}$. A significant reduction in $I_{DS,\text{max}}$ was observed as a function of the radiation.

Fig. 7.3 DC transfer IV of the HEMT showing a positive $V_T$ shift of $\sim 0.59$ V after the proton irradiation. The positive sign of $V_T$ shift is indicative of introduction of a negative charge in the AlGaN/GaN system that effectively reduces the 2DEG density under the gate thus requiring less negative bias to pinch-off the HEMT.
7.4 Radiation impact on HEMT DC IV characteristics

The application of proton irradiation causes a significant reduction (~0.2 A/mm) of drain current in the saturation regime as shown in Fig 7.2. This $I_{DS,max}$ drop is most likely due to the large positive and persistent $V_T$ shift ~0.59 V (see Fig. 7.3) occurring in these devices after the proton irradiation. The positive direction of $V_T$-shift is suggests occurrence of excess negative charge in the system induced by the radiation damage. This additional negative charge most likely under the gate terminal of the AlGaN/GaN structure, causes a reduction in the 2DEG density. A lower 2DEG density means that it is easier for the gate to pinch-off the channel. In other words we need apply less negative voltage to turn the transistor completely off. The sheet concentration of negative charge required to move the $V_T$ by the observed +0.59 V is calculated using a simple expression [13]–[15]:

$$n_T = \frac{\varepsilon_0 \varepsilon_{AlGaN} \Delta V_T}{q t_{AlGaN}}$$

(1)

where $\varepsilon_{AlGaN} = 8.9$ is the dielectric constant of AlGaN, $t_{AlGaN}$~ 30 nm is the AlGaN barrier thickness, $\varepsilon_0 = 8.854 \times 10^{-14}$ F/cm is the permittivity of free space, and $q = 1.6 \times 10^{-19}$ C is the charge of an electron. Using Eqn (1), an estimated negative sheet charge of ~$1 \times 10^{12}$ cm$^{-2}$ is calculated to give rise to the observed $V_T$-shift. We hypothesize that traps under the gate cause charge trapping and thereby cause the observed $V_T$ shift. For completeness we check for signs of formation/activation of access region traps by monitoring their effects on $R_{ON}$ and possibly $g_m$.  

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Fig. 7.4 Extrinsic $g_m$ plotted as a function of $V_{GS}$ for $V_{DS} = 2$ V before and after the proton irradiation. A clear positive shift in $V_T$ matching that observed in Fig. 7.3 was observed in the transconductance plots after the radiation. A minor reduction in peak transconductance suggests that the likely dominant contributor to the RF gain drop is the $V_T$ shift and not the $G_m$ drop. Additional insight from this result is that the degradation of the parasitic source access region in this HEMTs is minimal after the irradiation.

Fig. 7.5 Output IV showing triode regime of the HEMT operation before (black) and after (red) radiation for $V_{GS} = 0$ V and after radiation for $V_{GS} = +0.59$ V (magenta) case. The $V_{GS} = +0.59$ V corrects for the $V_T$-shift post-radiation thereby allowing selective measurement of the change in parasitic access region resistance. The observed change in the access regions is very small $<0.05$ Ohm-mm after radiation and is almost negligible in comparison the dominant and persistent $V_T$ shift observed.
7.5 Establishing under-gate effects and not access region effects as the dominant degradation mechanism in these devices

In order to investigate possible effects of the radiation on the parasitic access regions, additional measurements and analysis was performed. Figure 7.4 shows the extrinsic $g_m$ plot of the HEMTs before and after the electron irradiation. A shift in the $g_m$ peak was observed in the positive direction by $\sim 0.59$ V and this corresponds to the $V_T$ shift we discussed in the previous section. Only a minor decrease in the peak $g_m$ ($< 5\%$) was observed after the irradiation. For more insight, the expressions for $g_m$ are [16]:

$$g_{m,\text{int\,rinsic}} = \frac{\mu_0 e_0 e_{\text{AlGaN}}}{t_{\text{AlGaN}}} \frac{Z}{L_G} (V_{GS} - V_T), \text{...........................................(2)}$$

$$g_{m,\text{extrinsic}} = \frac{g_{m,\text{int\,rinsic}}}{1 + (g_{m,\text{int\,rinsic}} \cdot R_S)}, \text{...........................................(3)}$$

where $Z$ is the gate width, $L_G$ is the gate length, and $R_S$ is the parasitic source-access region resistance. Using Eqns (2), (3), and absence of $g_m$ degradation, we deduce:

1) There is little mobility degradation in these HEMTs after irradiation
2) The source access region resistance $R_S$ is unaffected after irradiation.

Figure 7.5 shows the output IV characteristics of the HEMT at $V_{GS} = 0$ V before and after the proton irradiation. The output IV at $V_{GS} = +0.59$ V of the HEMT after irradiation is plotted to correct for the $V_T$ shift effect. This correction allows for extraction of $R_{ON}$ changes due to the access regions. Little change ($<0.05 \, \Omega\text{-mm}$) in $R_{ON}$ suggested that the radiation damage mostly manifested through under-gate traps causing $V_T$ shifts and not thorough parasitic access region traps that affect $R_{ON}$ and $g_m$.  

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Fig. 7.6 Output pulsed IV pulsed from a quiescent bias condition of $V_{DS} = 0$ V, $V_{GS} = 0$ V using a dwell time of 5 $\mu$s and duty cycle < 1 %. The pulsed IV results may be considered complementary to DC IV results minus any self-heating effects. The drop in $I_{DS,max}$ observed here is more or less a ‘static’ degradation due to the proton radiation. It is called static because it is persistent and independent of switching condition or time.

Fig. 7.7 Pulsed transfer IV with quiescent condition $V_{DS} = 0$ V, $V_{GS} = 0$ V and dwell time of 5 $\mu$s. This pulsed IV captures the $V_T$-shift of 0.59 already observed in the DC IV results shown in Fig. 7.3. As described in text, this degradation is static or persistent in character.
7.6 Using pulsed IV to observe the ‘static’ $V_T$ shift effects

As already described in Chapter 2, the pulsed IV technique is a versatile approach complementary to the traditional DC IV characterization methods to obtain a deeper insight into the health of a HEMT as a function of stressors. Here we first perform the pulsed IV measurements from a $V_{GS} = 0$ V, $V_{DS} = 0$ V quiescent condition using a dwell time of 5 $\mu$s and a duty cycle of $<1\%$. The use of low duty cycle minimizes any effect of self-heating and should give the unadulterated electrical properties of the GaN HEMTs before and after the proton irradiation. The pulsed IV may be performed either in output IV mode as shown in Fig. 7.6 or transfer IV mode as shown in Fig. 7.7. The pulsed output IV results here were recorded for the $V_{GS} = 0$ V at room temperature before and after the proton irradiation. A significant degradation in maximum drain current by $\sim 0.22$ A/mm was detected as a function of the radiation consistent with the observation made in the DC IV as was already shown in Fig. 7.2.

To observe the corresponding $V_T$ shift, the pulsed transfer IVs were performed for $V_{DS} = 2$ V before and after the radiation and a positive $V_T$-shift of $\sim 0.59$ V was observed in agreement with the results from the DC IV data shown in Fig. 7.3. The $\sim 0.22$ A/mm of $I_{DS,\text{max}}$ drop and the corresponding $\sim 0.59$ V positive $V_T$-shift are persistent in nature. That is, this degradation does not disappear as a function of time. Nor is this degradation dependent on the quiescent bias conditions used. It is likely that these effects are due to very deep traps under the gate of the GaN HEMT. More discussion on this possibility will follow in a later section. We next discuss a second ‘dynamic’ degradation component in these GaN HEMTs induced by the proton radiation.
Fig. 7.8 Output pulsed IV with quiescent bias conditions of $V_{DS} = 0\,\text{V}$, $V_{GS} = 0\,\text{V}$ (solid black) and $V_{DS} = 20\,\text{V}$ and $V_{GS} = -4.5\,\text{V}$ (dotted red) and using a dwell time of 5 µs and duty cycle $< 1\%$. The difference between the solid black and dotted red lines is a measure of ‘dynamic’ degradation. This component which is dependent on the switching condition used, overlaps with the sold black curves when given enough time (> 100 s). This dynamic component is larger by $\sim 0.04\,\text{A/mm}$ after the proton irradiation.

Fig. 7.9 Pulsed transfer IV with quiescent conditions $V_{DS} = 0\,\text{V}$, $V_{GS} = 0\,\text{V}$ (solid black) and $V_{DS} = 20\,\text{V}$, $V_{GS} = -4.5\,\text{V}$ (dotted red) with a dwell time of 5 µs. In addition to the static $V_T$-shift component, an increase in the dynamic $V_T$ degradation of $\sim 0.1\,\text{V}$ was observed after proton radiation.
7.7 The ‘dynamic’ (time and switching dependent) degradation component detected using pulsed IV

Pulsed IV measurements can also be performed from different quiescent conditions. In Figs. 7.8 and 7.9 pulsed IV from quiescent condition $V_{GS} = -4.5 \text{ V}, V_{DS} = 20 \text{ V}$ (dashed red curves) is shown in addition to the $V_{GS} = 0 \text{ V}, V_{DS} = 0 \text{ V}$ (solid black) quiescent condition. Figure 7.8(a) shows the output pulsed IV for these two cases before any proton irradiation. The divergence between the dashed red lines and the solid black lines is here called the ‘dynamic’ component. This means that given sufficient time, the dashed red curves would overlap the solid black ones. The lower drain current in the dashed red case arises from the electron trapping induced by the off-state high $V_{DS}$ switching. Before radiation there was a 0.1 A/mm of $I_{DS,max}$ change which roughly corresponds to a $V_T$ shift of $\sim 0.28 \text{ V}$ [Fig. 7.9 (a)]. After irradiation, the dynamic change in $I_{DS,max}$ increases by 0.04 A/mm [Fig. 7.8(b)] and this change corresponds to an increase in dynamic $V_T$ by $\sim 0.1 \text{ V}$ [Fig. 7.9(b)]. This time and switching-dependent dynamic component occurs in addition to the static degradation component as summarized in Table 7.1. Because we established in section 7.5 that all these effects are simply manifestations of $V_T$ instability due to charge trapping under the gate, under gate defect spectroscopy was performed next to identify the specific trap(s) responsible.

<table>
<thead>
<tr>
<th>Degradation component</th>
<th>$\Delta I_{DS,max}$</th>
<th>$\Delta V_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static component</td>
<td>$\sim 0.22 \text{ A/mm}$</td>
<td>$\sim 0.59 \text{ V}$</td>
</tr>
<tr>
<td>Dynamic component (additional)</td>
<td>$\sim 0.04 \text{ A/mm}$</td>
<td>$\sim 0.10 \text{ V}$</td>
</tr>
</tbody>
</table>

Table 7.1 Summary of proton irradiation induced degradation in the GaN HEMT
Fig. 7.10(a) Gate controlled ClD-DLTS spectra plotted for 0.8 \( s^{-1} \) rate window using fill conditions \( V_{GS} = -4.5 \) V, \( V_{DS} = 20 \) V for 100 ms and measured at constant \( I_{DS} = 0.25 \) A/mm and \( V_{DS} = 2 \) V. Figure 7.10(b) shows Arrhenius data of the traps detected using the gate-controlled ClD-DLTS. Two electron traps \( E_C - 0.57 \) eV and \( E_C - 0.72 \) eV trap were detected before radiation and after radiation. No measured increase was observed in the \( E_C - 0.57 \) eV trap concentration as a function of radiation. However, a \( \sim 100 \) mV \( \Delta V_T \) increase was detected due to the \( E_C - 0.72 \) eV trap that explains the dynamic \( V_T \) component in Table 7.1. Arrhenius comparison to past work on bulk GaN suggests that both these traps most likely occur in the GaN buffer of the HEMT.
7.8 Investigating the origin of the dynamic degradation component using gate-controlled CI_D-DLTS methods

We first explore the origins of the \( V_T \) time dependent component using drain-controlled CI_D-DLTS sensitive to traps under the gate. Figure 7.10(a) shows the gate controlled CI_D-DLTS spectra of the GaN HEMT before and after proton irradiation. Before the radiation, two electron traps at \( E_C-0.57 \) eV and \( E_C-0.72 \) eV were detected. Arrhenius comparisons shown in Fig. 7.10(b) indicate that the \( E_C-0.57 \) eV is the same GaN buffer trap previously detected consistently in GaN HEMTs. We know from Chapters 3 and 4 that this level when active in the drain access regions, is chiefly responsible for the electrical-stress induced degradation in GaN HEMTs (i.e. in ones with high gate leakage). Interestingly, however, after the proton irradiation there was no measured increase in the concentration of the \( E_C-0.57 \) eV trap. This observation is consistent with irradiation studies on bulk GaN traps where again little impact was observed on the \( E_C-0.57 \) eV as a function of high energy particle irradiation [12]. The irradiation however has a substantial impact on the \( E_C-0.72 \) eV trap. The \( V_T \) associated with the \( E_C-0.72 \) eV trap changes by \(~100\) mV after irradiation and this change matches the additional \( V_T \) instability post-irradiation (see Table 7.1) detected using the fast pulsed IV. Arrhenius comparisons to previous irradiation work on bulk GaN traps, indicate that the \( E_C-0.72 \) eV trap also likely occurs in the GaN buffer. What’s more, the \( E_C-0.72 \) eV showed a high tendency of formation/activation after proton irradiation in both GaN bulk just as it does in the GaN HEMTs in this work.
Fig. 7.11(a) shows time response of the dynamic $V_T$ effect of the GaN HEMT before radiation when it is switched from $V_{GS} = -4.5$ V, $V_{DS} = 20$ V condition and measured at $I_{DS,\text{const.}} = 0.25$ mA/mm, $V_{DS} = 2$ V. The dashed vertical line indicates 5 µs, which is when the drain current is sampled in the room temperature ‘fast’ pulsed IV measurements shown in Fig. 7.11(b). The dispersion between the dashed red lines and the solid black lines in Fig. 7.11(b) is a qualitative measure of the total dynamic trapping effect induced by electrons trapped by both the Ec–0.57 and Ec–0.72 eV traps at short times (<5 µs).

Fig. 7.12(a) Shows that the ‘slow’ pulsed IV measurement samples data after 100 ms. Fig. 7.12(b) shows the corresponding ‘slow’ pulsed IV data that allows for emission of electrons from faster Ec–0.57 eV trap but still retaining the information of the slower Ec–0.72 eV trap. This method allowing us to selectively monitor the Ec–0.72 eV.
7.9 Slow pulsed IV: A technique to selectively study the effect of the slower (EC–0.72 eV) traps on terminal IV characteristics

A deeper understanding of the role of the EC–0.72 eV trap in the dynamic degradation component was obtained using ‘slow’ pulsed IV methods. The EC–0.57 eV is the faster traps with a 30 ms room temperature time constant whereas the EC–0.72 eV is the slower trap with an emission time constant of ~50 s at room temperature. A more direct discrimination of the impact of the slower EC–0.72 eV on IV characteristics is possible using a ‘slow’ pulsed IV technique that exploits this difference in emission time constants. Figure 7.11(a) shows that the fast 5 µs pulsed IV measurements captures the effect of electron trapping in both EC–0.57 eV and EC–0.72 eV traps. This is because the 5 µs time scale is much shorter than the characteristic emission time constants of both the traps as is clear from Fig. 7.11(a). The resulting dynamic $I_{DS,max}$ drop by 0.1 A/mm [see Fig. 7.11(b)] is therefore the total effect of the two traps. We know, however, that the EC–0.57 eV trap is mostly benign after irradiation and consequently is not responsible for the observed $V_T$ instability.

In order to focus entirely on the EC–0.72 eV trap, we use of a 100 ms dwell time as shown in Fig. 7.12(a). This long dwell time allows for almost complete emission (~99.95%) of the EC–0.57 eV trap leaving behind the signal exclusively from the EC–0.72 eV trap. The resulting slow pulsed IV shown in Fig. 7.12(b) then becomes a qualitative measure of the dispersion entirely due to the EC–0.72 eV trap. In the next section we look at the slow pulsed IV results before and after the proton irradiation.
Fig. 7.13 Slow (100 ms) output pulsed IV with quiescent bias conditions of $V_{DS} = 0$ V, $V_{GS} = 0$ V (solid black) and $V_{DS} = 20$ V and $V_{GS} = -4.5$ V (dotted red) and using a dwell time of 100 ms. The difference between the solid black and dotted red lines is a measure of ‘dynamic’ degradation exclusively due to the EC–0.72 eV trap. This dynamic component due to the EC–0.72 eV trap is larger by ~0.04 A.mm after the proton irradiation.

(a) Pre-irradiation

(b) After irradiation

Fig. 7.14 Slow (100 ms) transfer pulse transfer IV with quiescent conditions $V_{DS} = 0$ V, $V_{GS} = 0$ V (solid black) and $V_{DS} = 20$ V, $V_{GS} = 0$ V (dotted red) with a dwell time of 100 ms to capture dynamic $V_T$ effects exclusively due the EC–0.72 eV trap. The increase in the dynamic $V_T$ degradation of ~0.1 V listed in Table 7.6 is now directly linked entirely to the EC–0.72 eV trap.
7.10 Slow pulsed IV results before and after proton irradiation directly linking \( E_C-0.72 \) eV to the dynamic \( V_T \) degradation

Figure 7.13 shows the ‘slow’ pulsed output IV results of the GaN HEMTs before after proton irradiation using a 100 ms dwell time. As described in the previous section, such a switching scheme should only reveal trapping induced exclusively by the \( E_C-0.72 \) eV traps. The increase in deviation between the solid black curves (representing the \( V_{GS} = 0 \) V, \( V_{DS} = 0 \) V case) and the dashed red lines (representing the \( V_{GS} = -4.5 \) V and \( V_{DS} = 20 \) V case) by \( \sim 0.04 \) A/mm is very clearly an effect of the \( E_C-0.72 \) eV trap alone. The corresponding \( V_T \) shift associated with this \( I_{DS,\text{max}} \) dispersion is captured using slow pulsed transfer IV (shown in Fig. 7.13) in order to selectively measure dynamic \( V_T \) effects of the \( E_C-0.72 \) eV trap. The \( V_T \) change between the \( V_{GS} = 0 \) V, \( V_{DS} = 0 \) V case to the \( V_{GS} =-4.5 \) V, \( V_{DS} =20 \) V case increases by \( \sim 100 \) mV after the irradiation solely due to the \( E_C-0.72 \) eV defect. This \( \sim 100 \) mV \( V_T \) change is also consistent with the amplitude of \( E_C-0.72 \) eV peak from the gate-controlled CI\( \alpha \)-DLTS [Fig. 7.10 (a)]. In this manner, advanced trap spectroscopy in real operational GaN HEMTs has revealed a defect state at \( E_C-0.72 \) eV (likely in the GaN buffer) which has been directly correlated to device degradation through dynamic \( V_T \) instability induced by proton irradiation.

It is worth reminding the reader about the persistent \( I_{DS,\text{max}} \) drop (\( \sim 0.22 \) A/mm) and positive \( V_T \) shift (\( +0.59 \) V) still cannot be explained by either of the thermally detected traps at \( E_C-0.57 \) eV or \( E_C-0.72 \) eV. This we investigate in the following sections.
Fig. 7.15 Schematic cross-section of the 2-terminal AlGaN/GaN Schottky diode used in the radiation study.

(a) CV results from AlGaN/GaN Schottky diode for different proton fluence and (b) $V_T$-shift extracted from the CV of the Schottky diode compared against the $V_T$ shift from the HEMT IV. Similar $V_T$ degradation occurs in the diodes, and the HEMTs establishing these simple structures as are reasonable tools to establish an understanding the $V_T$-shift effect in the HEMTs.
7.11 Exploring the persistent positive $V_T$ shift after proton irradiation on simple 2-terminal AlGaN/GaN Schottky diodes

The operational GaN HEMTs have a three terminal geometry consisting of intricate field plate designs, SiNx-passivated access regions, and complex and lateral and vertical electric fields. Therefore in order to verify whether the $V_T$-shift post-radiation is unique only to such HEMTs, proton radiation experiments were performed on simple Schottky gate AlGaN/GaN heterostructures. These diodes were grown using plasma assisted molecular beam epitaxy (PAMBE) and consist of 290 µm x 290 µm with Ni/Au Schottky gates and annealed Ti/Al.Ni/Au Ohmics contacting the 2DEG. A schematic cross-section of the Schottky diodes studied here is shown in Fig. 7.15.

The AlGaN/GaN Schottky diodes were subjected to different doses of 1.8 MeV proton irradiation at 5x10$^{12}$, 1x10$^{13}$, 3x10$^{13}$, 5x10$^{13}$ and 1x10$^{14}$ cm$^{-2}$. A positive shift of threshold voltage $V_T$ in the Schottky diodes was observed using CV measurements as shown in Fig. 7.16(a). The extracted $V_T$-shift for the Schottky diode was compared against that obtained from the IV measurements on the GaN HEMTs [Fig. 7.16(b)]. A similar amount of $V_T$ shift was observed in both the heterostructures and the HEMTs at 1x10$^{14}$ cm$^{-2}$ proton fluence despite being grown and fabricated differently, at different times, and at distant facilities. Similar reports have been made positive $V_T$-shifts induced on proton irradiated heterostructures in past [17]. These facts allow us to use the diode structure from this point as a vehicle to carefully study the origins of this almost universal positive $V_T$ shift phenomenon after proton irradiation.
7.12 Factors that could affect $V_T$ of an AlGaN/GaN system

Having clearly observed the $V_T$ shifts in Schottky diodes, the role of the access region SiN$_x$ passivation in the GaN HEMTs in the static $V_T$ shift phenomenon can be ruled out. This also means that the physical location of whatever is causing the $V_T$ shift is entirely beneath the Schottky metal gate because the AlGaN/GaN diode is essentially an ‘all gate’ device with almost negligible ungated or access regions. The expression below represents the various parameters under the gate that could affect the $V_T$ [18]–[19]:

$$V_T = \frac{\phi_B}{q} - \frac{\Delta E_C}{q} \frac{d \cdot \sigma}{\varepsilon_{AlGaN}} - \frac{E_{fo}}{q} \frac{d \cdot Q_{AlGaN}}{2\varepsilon_{AlGaN}} - \frac{d \cdot Q_{it}}{\varepsilon_{AlGaN}} - \frac{Q_{GaN}}{C_{effective}} (7.1)$$

where $\phi_B$ is the Schottky gate barrier height, $\Delta E_C$ is the AlGaN/GaN conduction band offset, $\sigma$ is the polarization sheet charge, $E_{fo}$ is the band bending of the GaN at the

Fig. 7.17 Equilibrium energy band diagram defining the different components listed in Equation 7.1. The blue dashes denotes the negative bulk (AlGaN or GaN) trapped charges in the system whereas the blue band at the interface denotes the negative interface trapped charge. The red bar represents the negative sheet polarization charge.
AlGaN/GaN interface referred with respect to the Fermi level (see Fig. 7.17), $Q_{AlGaN}$ is the charge in the AlGaN barrier, $Q_{it}$ is the charge in the AlGaN/GaN interface and $Q_{GaN}$ is the charge in the GaN buffer. We examine each of these component and their role on $V_T$

### 7.13 Effect of parameters $\phi_B$, $\Delta E_C$, $\sigma$, and $E_{fo}$ on $V_T$-shift

Internal photoemission (IPE) measurements before and after irradiation reveal that the Schottky barrier height $\phi_B$ is practically unchanged at ~1.3 eV with the proton irradiation thereby eliminating $\phi_B$ as a possible suspect behind the $V_T$-shift.

Next, it is argued that the number of atomic displacements due to the proton bombardment upto $1 \times 10^{14}$ cm$^{-2}$ fluences is far too small to cause a significant change to the conduction band offset $\Delta E_C$ or the polarization sheet charge $\sigma$ both of which should be constant for a given AlGaN/GaN system with a given amount of mechanical strain built into it. Also, once the 2DEG is formed in the AlGaN/GaN system, there should be very little change (in the order ~ mV) in the $E_{fo}$ and certainly not enough to produce the large voltage changes (~0.5 V) that affect the $V_T$ as observed experimentally. With Schottky barrier height, band-offset, $E_{fo}$ and polarization charge eliminated as sources for the $V_T$ shift, the cause of this effect could only be due to additional negative charges trapped in the structure after the irradiation. We now discuss some computer aided numerical simulations using Atlas Silvaco wherein several scenarios were considered with negatively charged traps assumed in the different layers of the AlGaN/GaN system and interfaces to test the feasibility of each case.
Fig. 7.18(a) Cross-section of the simulated AlGaN/GaN Schottky diode in Atlas Silvaco and a (b) magnified view clearly showing the active epi-layers and listing the different cases being simulated.
7.14 Silvaco modelling to determine location of deep traps causing the static $V_T$-degradation effects

Having established in the previous section that traps are the possible mechanism causing the $V_T$ shift in both the AlGaN/GaN HEMTs and Schottky diodes, the next step was to determine in which layer the dominant defects affecting $V_T$ actually occurring. To do so an Atlas Silvaco based virtual AlGaN/GaN Schottky diode was modeled as shown in figure 7.18. The traps was assumed separately in three different layers and their effect on the simulated CV curves and subsequently, the $V_T$ was modeled and compared against the measured $V_T$ shift results.

Before discussing the simulation results for each case, it is prudent to first appreciate the following facts concerning deep trap formation in n-GaN. These statements are based on proton irradiation work by Zhang et. al. on bulk n-type GaN [12]:

1) Proton irradiation creates deep acceptor levels at $E_C$–3.25 eV and $E_C$–1.25 eV that act as compensating centers causing free electron removal.

   - Significance here: We will assume in the simulations such deep acceptor traps $E_C$–3.25 eV (for GaN) and $E_C$–3.7 eV (for AlGaN) to simulate the proton-irradiation induced degradation in the III-N system

2) The introduction rate of defects in n-type GaN with protons is $\sim$500 cm$^{-1}$.

   - Significance here: This quantity is expected to remain unaffected to change in III-N alloy compositions, because to an incoming energetic proton, GaN and its alloys should more or less ‘look’ like the same material.
7.15 Eliminating the $Q_{AlGaN}$ and $Q_{it}$ effect on the $V_T$ expression

At first, an $E_C-3.7$ eV electron was assumed in the AlGaN bulk. In order to produce the magnitude of $V_T$ shift observed in the measurements after $10^{14}$ cm$^{-2}$ proton dose, an extraordinarily large defect introduction rate of $\sim$10000 cm$^{-1}$ had to be assumed. As a separate case, an $E_C-3.25$ eV trap was assumed over a 0.5 nm region of the GaN close to the AlGaN/GaN interface. Yet again, a massive introduction rate of $\sim$240000 cm$^{-1}$ had to be used to match the measured $V_T$ shift at the highest dose. In the previous section we mentioned that the introduction rate for traps from bulk n-GaN studies is only 500 cm$^{-1}$ [12]. It is therefore highly unlikely that the defect introduction rate in the AlGaN bulk or at the interface be so high. Moreover, in both cases, the simulated $V_T$ has a linear dependence to fluence (see Fig. 7.19) unlike the measured data. The simulations reveal that trapping in AlGaN or interface cannot predict the measured $V_T$ shift behavior.

![Fig. 7.19 Simulation of effect of negative trapped charges in AlGaN bulk and in AlGaN/GaN interface. Very large defect introduction rate ($\sim$20x for case AlGaN traps and $\sim$400x for interface traps) compared to measured introduction rate of 500 cm$^{-1}$ in bulk GaN. Also, the simulation of traps in AlGaN and interface reveal a linear dependence on proton fluence, a trend the measured data clearly does not follow.](image-url)
Fig. 7.20 Simulation of $V_T$ shift effect in the AlGaN/GaN Schottky diode using a defect introduction rate of 500 cm$^{-1}$ in the bulk GaN. An acceptor level at $E_C-3.25$ eV was assumed uniformly in the GaN layer. The measured and simulated data show excellent agreement in $V_T$ amplitude over the entire range of the proton fluences. This result strongly suggests that the offensive traps causing the static $V_T$ shift in the AlGaN/GaN HEMTs and heterostructures occur in the GaN buffer.

Fig. 7.21 Simulated equilibrium band diagrams through a vertical cutline under the Schottky gate of the AlGaN/GaN system (a) before and (b) after $1\times10^{14}$ cm$^{-2}$ proton irradiation. In case (b), a large concentration ($5\times10^{16}$ cm$^{-3}$) of $E_C-3.25$ eV trap was introduced in GaN, so much so that it exceeded the n-type GaN background doping ($\sim1\times10^{16}$ cm$^{-3}$). The excess acceptor traps causes carrier removal and band-bending, thereby reducing the 2DEG density at the AlGaN/GaN interface through a back gating effect. It is this carrier removal and the associated pronounced band-bending that is responsible for the persistent $V_T$ shift in the AlGaN/GaN HEMTs after proton irradiation.
7.16 GaN buffer traps as the possible source of the persistent $V_T$ degradation

Having established that the $V_T$ shift phenomenon cannot be explained using AlGaN or interface traps, the only remaining option was now to consider the traps occurring in the GaN buffer. Monte Carlo simulations of the 1.8 MeV protons bombardment experiment in GaN reveals a 20 µm penetration depth. It is reasonable, therefore, to assume that the defects are distributed uniformly throughout the first few microns of the nitride films. As discussed in the previous section, such low introduction rates don’t generate enough traps in the AlGaN or the interface to warrant the 0.59 V $V_T$ shift. However in the GaN, a $1\times10^{14}$ cm$^{-2}$ fluence at a 500 cm$^{-1}$ introduction rate can create $\sim5\times10^{16}$ cm$^{-3}$ additional defects in the material distributed over many microns. The acceptor trap assumed here for purposes of simulation is the $E_C–3.25$ eV trap. The $V_T$ shifts from the simulated CV curves of the structure were compared against the measured $V_T$ shifts to give an excellent match over the ranges simulated (see Fig. 7.20). This match in trends suggests that the GaN buffer traps indeed are responsible for causing the persistent positive $V_T$ shift.

Figure 7.21 describes a possible model for occurrence of the $V_T$ shift. As seen in Fig. 7.21(a), when the trap concentration is below $1\times10^{16}$ cm$^{-3}$ background n-type doping, the band diagrams are almost unaffected. At relatively low trap concentrations ($<1\times10^{16}$ cm$^{-3}$), the GaN buffer Fermi level position is close to conduction band, thus the depletion region in GaN is small, and the $V_T$ is insensitive to the acceptor density in GaN.
However when the trap concentration increases above $1 \times 10^{16}$ cm$^{-3}$, like for instance in 7.21(b) which represents the energy band diagrams for trap concentrations $\sim 5 \times 10^{16}$ cm$^{-3}$, the $V_T$ shifting mechanism becomes prominent. In such cases, the Fermi level of the GaN buffer starts to move toward valence band, causing a substantial increase in GaN band bending and reduced 2DEG density. The Fermi level becomes pinned at the deep acceptor level and the depletion region inside GaN widens. Adding more acceptors to GaN buffer at this stage compensates the 2DEG further and leads to an even more positive $V_T$ shift. To summarize, the Silvaco simulations reveal that the acceptors in GaN buffer can cause $V_T$ shift through moving GaN Fermi level position and compensating 2DEG, but this effect is significant only when acceptor density is larger than the background n-type doping concentration in the GaN buffer layer.

### 7.17 Summary and Conclusions

The results of the proton irradiation on the GaN HEMTs and hetrostructures are quite interesting and clear. Two primary degradations components were identified. A larger persistent threshold voltage shift is likely due to very deep the $E_C-1.25$ and $E_C-3.25$ eV traps. Modeling of the impact of the deep levels predicts the dependence on fluence giving evidence proof that GaN buffer traps are indeed responsible. A second, a $V_T$ dispersion increase due to the $E_C-0.72$ eV was linked to GaN buffer trap when compared to previous reports on bulk proton irradiated bulk GaN. It is interesting to note is that most of the radiation effects apparently seemed to affect traps under the gate and threshold voltage unlike electrical stressing which seemed affected traps in the drain.
access regions and the on-resistance. A critical comparison of electrical stressing to radiation will be presented in the next and final chapter of this dissertation.

7.18 References


Chapter 8

Conclusions and future directions

The goal of this work has been to develop precise links between specific defects within the component films of operational GaN HEMTs and their role in device performance and lifetime degradation as a function of electrical stressors and high energy particle induced stressors. On a case by case basis, the kind of stressor used, the type of degradation observed, and design of target device under test, each offered a unique set of challenges all insurmountable using the conventional trap spectroscopy methods typically applied to GaN materials and transistors [1]–[3]. To enable the objectives of this work, the suite of CID-DLTS/DLOS trap spectroscopy methods and models first developed for GaN HEMTs in 2009 [4]–[5] had to be expanded. For this purpose, a more formal redefinition of the gate-controlled and drain-controlled switching schemes of original CID-DLTS/DLOS was developed with a goal of observing consistent and quantitative trap results (especially in terms of defect concentrations) across multiple devices received from a range of sources. This second generation CID-DLTS/DLOS methods were then successfully applied to RF stressed HEMTs before and after RF accelerated life testing and before and after proton irradiation [6]–[12]. To facilitate trap measurements on GaN-on-Si power MISHEMTs, a third generation of the same CID-DLTS/DLOS methods had
to be developed to accomplish high voltage switching up to 600 V [13]. In addition to the CID-DLTS/DLOS methods, several other innovative and original experimental techniques and methodologies were created to complement it with an objective of learning the location and physical properties of defects and their impact on device terminal characteristics. Methods such as lighted IV discussed in Chapter 5, and slow pulsed IV described in Chapter 7 have not just supported the CID-DLTS/DLOS measurement by acting as independent sources of validation, but also serve as a quick non-invasive trap spectroscopy tools within themselves allowing rapid survey and screening of GaN HEMTs based on their trap properties. The application and continued testing and development of the very versatile nano-DLTS/DLOS methods to such increasingly exotic and complicated HEMT devices and materials structures serves an additional fall out to this research effort. Using this expanded palette of trap spectroscopy tool kit, real operational GaN HEMTs with different configurations and varied target applications were investigated to discern the role of traps in their degradation as a function of very different but very relevant stressors. A very clear difference in degradation of GaN HEMTs was observed as a function of different stressors, GaN HEMT design, and other aspects of operational history. At least three distinct degradation mechanisms due to the action of traps in the III-N bandgap were identified as a function of RF stressing [6]–[10], high voltage application [11], [12], and proton irradiation [13], respectively. Another major contribution of this work is the expansion of the taxonomy of dominant defects detected in GaN HEMTs and unambiguous assignment their physical location to a specific component layer of the device structure. Models were proposed wherever
necessary to help describe the role of these defects in the device degradation and long term device reliability inhibition. The following sections details the specific results for each of these cases.

8.1 Traps affecting RF electrically stressed HEMTs

From a range of RF GaN HEMTs received from at least 6 different suppliers, a consistent picture has emerged so far regarding traps in the drain access regions of RF stressed GaN HEMTs and their role in degradation on on-resistance [6]–[10]. It is believed that the existence of high electric fields at the gate edge or the edge of the field plate of the HEMT leads to formation or activation of pre-existing defects in the III-Nitride material. The $R_{ON}$ degradation and corresponding reduction in RF output power characteristics may be brought about through increased action of upper bandgap states (which are usually faster emitting) or through mid-gap or lower band gap states (which for a given temperature emits at a much slower rate compared to the upper band gap states). Depending on what kind of trap is involved (slow or fast), the recovery time of the degraded on-resistance can be very different. In Chapters 3 and 4 we saw that the trapping action in the GaN HEMT drain access regions was mostly due to the $E_C-0.57$ eV trap in the GaN buffer. The characteristic thermal response time of this trap at 300 K is around 30 ms which is slow enough to degrade the RF switching performance of the GaN HEMT but fast enough to be captured in terminal switching measurements in reasonable amounts of time. However it was also observed that the $E_C-0.57$ eV GaN buffer trap was modulated and consequently detected only in devices whose reverse gate leakage exceeded a particular threshold. Experimentally this value has been observed to be $\sim 10^{-7}$.
A/mm. For GaN HEMTs that have much lower reverse gate leakage, the $E_C-0.57$ eV GaN buffer trap is starved of electrons and is therefore not modulated or detected. This does not mean that the trap is entirely absent. It just means that the filling mechanism to this trap has been greatly inhibited. As a result the trap cannot participate in the RF output power degradation of the transistors.

However in GaN HEMTs with very low reverse gate leakage, with negligible $E_C-0.57$ eV trap activity, other much deeper traps participated in the producing the persistent $R_{\text{ON}}$ increases. Very deep traps capturing electrons in the drain access regions have characteristic emission times ranging from a few hours to several centuries. In the time scale of measurements of the GaN HEMTs and in the dark, the effects of these very deep traps may seem persistent or permanent. In Chapter 5 we saw a clear example of how a broad state of deep traps in the $E_C-1.6$ to $2.5$ eV range participated in persistently increasing the on-resistance. Lighted output IV measurements were performed to experimentally correlate the persistent increase in on-resistance to the drain controlled $\text{Cl}_\text{D-DLOS}$ detected deep levels close to the mid gap. Unlike the more leaky HEMTs where the $E_C-0.57$ eV GaN buffer trap showed more activity, in these lower leakage GaN HEMTs the output power degraded thanks to the increase in concentration of the deeper levels. These observations indicate why it is necessary to continue probing the GaN HEMTs comprehensively throughout the bandgap using a combination of both the thermal and optical methods to identify the dominant defects directly responsible for the degradation.
8.2 Trap induced degradation due to high energy proton irradiation compared to RF electrical stressor

In Chapter 7 we saw that high energy proton irradiation induced two distinct components of HEMT degradation both mostly related to traps under the gate. The larger more persistent degradation components was a persistent positive threshold voltage shift of ~0.6 V at 1x10^{14} cm^{-2} fluence of 1.8 MeV protons. It was systematically proved that the traps under the gate were necessary to produce the desired $V_T$ shift. Arguments concerning the magnitude of volumetric trap concentrations required to produce this $V_T$ shift were used to systematically eliminate the AlGaN barrier or AlGaN/GaN interface as the potential sources for the $V_T$ shift leaving behind only the GaN buffer as the possible suspect layer. Direct comparisons were made to DLOS studies made on proton irradiated n-type GaN in literature to identify levels at $E_C$–1.3 and 3.25 eV that tend to increase in concentration as a function of the proton irradiation [14]. Computer simulations using Atlas Silvaco revealed that if the concentrations of the deep traps exceeded the doping of the GaN buffer layer then the subsequent carrier removal and back gating could cause a reduction of 2DEG density at the AlGaN/GaN interface that could explain the observed $V_T$ shift. A second smaller a $V_T$ time and switching dependent component increase due to an $E_C$–0.72 eV GaN buffer trap under the gate. This direct connection was made using a combination of gate-controlled ClD-DLTS and slow pulsed IV methods as described in Chapter 7. Although the $E_C$–0.57 eV was also detected in these HEMTS using gate-controlled ClD-DLTS, its concentration remained unchanged as a function of radiation. An interesting footnote is that the $E_C$–0.57 eV trap signature in previous [14] GaN studies
For a given proton fluence, similar number of traps are created under the gate and in the drain access regions. However due to the non-linear relation between \( n_T \) and \( R_D \), the effect on \( V_T \) is much larger and observed far more readily than any effect on \( R_{ON} \).

Fig. 8.1: For a given proton fluence, similar number of traps are created under the gate and in the drain access regions. However due to the non-linear relation between \( n_T \) and \( R_D \), the effect on \( V_T \) is much larger and observed far more readily than any effect on \( R_{ON} \).

Fig. 8.2: Schematic showing key differences between (a) irradiation induced trap degradation and (b) RF stress-induced trap degradation in AlGaN/GaN HEMTs. While in irradiated HEMTs, trap formation occurs uniformly throughout the AlGaN and GaN films, the critical traps causing the \( V_T \) instabilities are the located under the gate. In the RF stressed HEMTs, however, formation or activation of traps occurs locally at the gate rain edge. The contrasting trap formation between proton irradiation and RF stressing indicates that these different stressors impact GaN HEMTs in very different ways.
also remained unaffected by the proton irradiation whereas the $E_{C}-0.72$ eV showed significant increase post irradiation in both in the irradiated bulk GaN and the GaN HEMTs. Drain controlled $C_{I_D}$-DLTS/DLOS measurements in the HEMTs before and after the irradiation revealed an increase in concentration of the $E_{C}-0.72$ eV trap in the drain access regions comparable to that under the gate. However this increase in the $E_{C}-0.72$ eV concentration was not large enough to produce a large $R_{ON}$ change in the HEMTs. The total $R_{ON}$ change in these devices <0.05 $\Omega$-mm. This observation leads us to a very important conclusion. For a given radiation fluence, and therefore, for the same number of traps created uniformly under the gate and in the parasitic access regions, it is the trapping under the gate that will manifest as a bigger degradation effect on the GaN HEMT through $V_T$ instability than through $R_{ON}$ changes. This effect is quantitatively summarized in Fig. 8.1.

In short what this tells us is that it is not uncommon for GaN HEMTs subjected exclusively to particle irradiation alone to suffer mostly from $V_T$ shifts and other $V_T$ related instabilities than increased $R_{ON}$ effects. Such a degradation mechanism is very different from the electrically stressed GaN HEMTs where high electric fields localized at the gate-drain edge preferentially activates traps only in the drain access region and affects the parasitic drain access region resistance $R_D$. A schematic representation of these key differences identified so far between the proton irradiation and RF electrical stressing is shown in Fig. 8.2.

Another noteworthy difference is in the participant defect signatures causing degradation as a function of radiation stressor versus RF electrical stressor. In Chapters 3
and we saw that if the GaN HEMTs have sufficient leakage (>10^{-7} A/mm) then it is the $E_C-0.57$ eV trap that is directly responsible for the on-resistance degradation and output power degradation after the RF electrical stressing. However, for the radiation case the $E_C-0.57$ eV trap was hardly affected and instead the $E_C-0.72$, 1.3 and 3.25 eV traps were correlated to the observed $V_T$ degradation due to their activity under the gate.

### 8.3 Trap induced degradation due to high voltage application

Enormous strides have been made in the solving problems concerning trap spectroscopy of high voltage GaN HEMTs for power switching applications. [13] In Chapter 6 we discussed the extension and application of the ClD-DLTS/DLOS approaches, typically to RF GaN HEMTs (up to voltages <50 V), to GaN-on-Si power devices switched up to 600 V. In the early generation of MISHEMTs received a very large dynamic $R_{ON}$ was observed when the device was switched over off-state $V_{DS}$ of 200 V. Knowing that the electric fields in the device peak at the edge of the longest field plate at such high voltages, it was deduced that the $R_{ON}$ degradation phenomenon was due to severe localized trapping effects in the drain access region at the field plate edge. When switched back to low voltages, the recovery of the dynamic $R_{ON}$ took several hours (> 3 hours) and did not show evidence of a thermally dependent time constant. Suspecting a very deep trap, optical based high voltage ClD-DLOS was performed to detect an $E_C-2$ eV trap as directly responsible for the massive current collapse effect during high off-state $V_{DS}$ switching. Using a combination of CC-DLOS and nano-DLOS on a corresponding Schottky gate heterostructure, in conjunction with reports in literature [15] on $E_C-2$ eV trap in bulk GaN, the physical location of this trap was unambiguously
established in the GaN buffer. A back-gating based model was presented to describe how the $E_C - 2$ eV possibly causes the severe localized 2DEG removal that leads to high dynamic $R_{ON}$ values for extended periods of time. This work demonstrates (once again) the paramount role buffer traps can play in GaN HEMT performance and reliability degradation irrespective of its target application.

8.4 Future directions

Now that canonical GaN HEMT devices for RF and power switching have been characterized as a function of individual stressor, say RF operation, or high voltage, or high energy particle irradiation, the next step would be combine these stressors and track the presence and properties of these traps in the very same HEMTs. These experiments would leverage on existing understanding of single stressor induced degradation mechanisms in order to separate out effects occurring in a combined stressor environment which represents real world operation better. As far as high energy particle radiation goes, efforts are already underway to understand electron irradiation effects on baseline GaN HEMTs. Trap work on HEMTs subjected to combined electrical stressing and particle irradiation (electron or protons) is the next step.

There has also been much debate in literature on the comparability of RF and DC stressing and their differential impact on GaN HEMT performance, trapping, and reliability. [16]–[18] Given that DC stressing conditions can be more readily implemented with little equipment overhead, comprehensive trap studies in this regard would be highly useful. However, no clear consensus has been reached as to whether DC electrical stressing is a valid proxy to RF accelerate life testing. As a first step in
understanding the differences between DC and RF stressing from a trap formation/activation perspective, commercial L-band GaN HEMTs were subjected to DC and RF stressing using nominally identical semi-ON state quiescent conditions. The degradation results observed for each case was very different. While the RF stressing proved to be mostly benign, the DC stressing produced persistent $V_T$ shift of $\sim 160$ mV effects suggesting very deep trap formation under the gate. Early gate controlled CID-DLOS measurements have revealed formation/activation of a deep trap at $E_C-1.4$ eV as directly responsible for the increased positive $V_T$ shift. Additional measurements are presently underway to further investigate the reasons behind the observed differences in degradation and in trap formation.

Also untapped is the possibility of CID-DLTS/DLOS methods as a tool to investigate transistors fabricated from novel III-nitrides material systems. Already in this dissertation work we have investigated InAlN barrier HEMTs, and N-polar GaN HEMTs. Aside from these, a whole array of devices in research phase exist such as enhancement mode HEMTs, N-rich HEMTs, non-polar HEMTs, all of which have hardly been investigated in terms of traps from a materials perspective let alone from a device perspective. The CID-DLTS/DLOS methods and models will serve in many ways as the missing link between the material scientist and the device engineer in terms of the interdependence of these disciplines in matters of deep trap activity. Thus, at the culmination of this work, we are poised to explore several new and exciting possibilities of application of these methods some of which have been listed above and several of which have not even identified yet. This understanding of deep traps acquired using the
HEMT as a vehicle to study the material can be applied directly into improvement of GaN material quality thus benefitting a whole array of nitride based devices far beyond the presently defined realms of GaN electronics.

8.5 References


Bibliography


