Deep trap-induced dynamic on-resistance degradation in GaN-on-Si power MISHEMTs

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Abstract— Identification and characterization of a single, deep trap causing large increases in the on-resistance of GaN-on-Si power metal-insulator-semiconductor-high electron mobility transistors (MISHEMTs) is reported. This is achieved by using HEMT-based deep level optical spectroscopy (DLOS) and related methods in conjunction with high voltage off-state V_{DS} switching up to 400V. A trap with an activation energy of $\sim E_C - 2$ eV that is physically located in the drain-access region of the MISHEMTs is shown to be the primary source of an increase of the dynamic on-resistance increase by as much as ~ 9 times at 400 V operation. Comparisons of trap signatures extracted from the MISHEMT with capacitance-based DLOS measurements of simple Schottky-diode test-structures showing the same, dominant trap signature suggests that the physical defect is located within the GaN buffer and is not a surface or insulator-related defect. A buffer trap based model is presented to explain the observed on-resistance degradation effects in the MISHEMTs during high voltage switching.

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

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1. Introduction

GaN high electron mobility transistors (HEMTs) are at the cusp of revolutionizing power electronic devices thanks to their low channel resistances, large breakdown fields, and low stored charge that enables fast and highly efficiency switching operation at high voltages [1-5]. These benefits coupled with cost-advantages of growing on Si substrates have enabled commercialization of GaN-based HEMTs in large volumes for high voltage switching applications [1, 2]. Despite the progress in achieving high quality epitaxy of III-Nitride semiconductors on Si, the problem of minimizing crystal defects (point and extended) in the III-Nitride films is still not trivial [6, 7]. Defects can manifest as deep states in the energy bandgap that participate in charge trapping and thereby degrade HEMT performance and affect their long-term reliability [8–16]. Furthermore, the behavior of traps in high field conditions for power GaN HEMTs is not well understood where the application of high voltages itself may also lead to formation/activation of additional electrically active defects. To date there have been sparse studies on trapping effects in GaN-on-Si metal-insulator-semiconductor high electron mobility transistors (MISHEMTs) and fewer still directly correlating the high voltage switching impact on device metrics to traps [17, 18]. One figure of merit power engineers are particularly concerned with is the transistor ON-resistance, R_{ON} [2, 4, 17–20]. Dynamic R_{ON} is a time-dependent change in resistance observed after switching from a high off-state drain-to-source voltage (V_{DS}) condition. This *dynamic* R_{ON} , over time, recovers to a *steady-state* R_{ON} condition that matches the resistance originally measured in the virgin HEMT, and thus traps are a very likely source for this degradation [2, 4, 17–20].

Therefore, the purpose of this study is to identify traps in Ga-on-Si power MISHEMTs at meaningful operating conditions, i.e. at high voltage operation, and to correlate their behavior with observed modes of device degradation. To achieve this, we report here the successful adaptation of the defect spectroscopy methods known as constant drain current deep level optical spectroscopy and deep level transient spectroscopy (CI_D -DLOS/DLTS), which have enabled direct connections between specific traps and degradation modes of AlGaN/GaN RF HEMTs, to now be applicable for high voltage switching studies, achieving measurements of up to a V_{DS} of 600 V in off-state switching. A dominant deep trap, at $E_C - 2.0$ eV is revealed as the root cause of complete current collapse under high voltage switching for the GaN-on-Si MISHEMTs studied here. These observations represent an entirely different degradation mode compared with RF GaN HEMTs studied to date[11]-[16]. Additional defect spectroscopy studies of AlGaN/GaN on Si heterostructures processed into simple Schottky diodes suggest that this trap exists only within the GaN buffer and further analysis shows it to be activated only in the drain access region extending beyond the field plates of the MISHEMT.

2.Experimental

The transistors described in this study are AlGaN/GaN HEMTs grown on 6-inch Si (111) substrates with dielectric in the access regions and under the gate. The buffer design of these devices is similar to what has been published in prior reports of high voltage GaN-on-Si MISHEMTs [2], and [3]. The $Al_xGa_{1-x}N$ barrier had thickness of ~30nm with Al composition of ~25%. The barrier was grown on an unintentionally

doped GaN buffer of thickness ~ 150 nm which in turn was grown on a semi insulating GaN buffer layer of ~ 1 μm . These MISHEMTs had multiple field-plates placed in a stairway fashion along the gate-to drain access region. The dimensions of these field plates were optimized to achieve a breakdown voltage in excess of 600 V. The maximum drain current at $V_{GS}=0\text{V}$ was ~ 0.45 A/mm. The 2DEG concentration and mobility measured by Hall Effect measurements on vanderPauw structures were $1 \times 10^{13} \text{ cm}^{-2}$ and $1900 \text{ cm}^2/\text{Vs}$, respectively. A separate part of the same wafer (as the MISHEMT) but with no insulating dielectric was used to fabricate semi-transparent Schottky diode test-structures using a process described elsewhere [21].

Thermal and optically assisted de-trapping phenomena in the fully processed MISHEMTs were investigated using modified CI_D -DLTS/DLOS methods [11–16]. The transistors measured here are switched from pinch-off with $V_{GS} = -10$ V and off-state V_{DS} (ranging from 10V to up to 400V) for 100 ms. Following the fill pulse, V_{DS} is dynamically controlled to maintain a constant drain-current $I_{DS, \text{const.}} = 0.42$ mA/mm in the triode regime with $V_{GS} = 0$ V from 2×10^{-3} s to 10^4 s. This high V_{DS} off-state fill pulse promotes electron trapping in the drain access region, the effect of which is then recorded as a V_{DS} transient during the measurement phase. The resulting V_{DS} time-transient may be converted to an R_{ON} time-transient (with units of $\Omega\text{-mm}$) using the simple relation $R_{ON} = \Delta V_{DS} / I_{DS, \text{const.}}$. The R_{ON} transients are recorded at different temperatures for the same off-state V_{DS} ($=250$ V here). To extract individual trap time constants and signal amplitude, isothermal box-car DLTS analysis [22, 23] was performed on the R_{ON} transients. The resulting isothermal CI_D -DLTS spectra for each temperature provides a spectrum of the characteristic time constant(s) τ of the participating trap(s). The box-car

analysis was performed 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 β ($= 2.5$ 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 isothermal CI_D -DLTS plots were created using the expressions:

$$\Delta R_{ON} = \left(\frac{\beta^{\beta/(\beta-1)}}{\beta-1} \right) * [R_{ON}(t_1) - R_{ON}(t_2)] \dots \dots \dots (1)$$

$$\tau = (t_2 - t_1) / \ln(t_2 / t_1) \dots \dots \dots (2)$$

where $R_{ON}(t_1)$ and $R_{ON}(t_2)$ are the values of on-resistance recorded at times t_1 and t_2 respectively. For an electron emission process, the $R_{ON}(t_2) < R_{ON}(t_1)$, the calculated ΔR_{ON} values plotted are negative in sign according to the convention adopted in Eqn (1). The first term in Eqn(1) is a correction factor [22, 23] required to account for the full amplitude of the R_{ON} transient (assuming a pure exponential decay process). For $\beta = 2.5$ this correction is ~ 3.07 . The isothermal R_{ON} transients measured at different temperatures can be used to extract the signature activation energy and thermal capture cross-section of the traps responsible [22, 23]. The thermal based methods are sensitive to drain-access region traps having thermal activation energies less than approximately 1 eV due to temperature limitations of the cryogenic stage.

To probe even deeper drain-access region traps that are not easily thermally activated, drain-controlled CI_D -DLOS was performed where the sample is illuminated with a tunable sub-bandgap monochromatic light source to enable photoionization of the deeper levels. For the CI_D -DLOS measurements, the MISHEMT was switched using a fill pulse of $V_{GS} = -10$ V and $V_{DS} = 250$ V for 10 s, and this fill pulse was followed by a measurement in the linear regime at a constant current of $I_{DS} = 0.42$ A/mm at $V_{GS} = 0$ V.

The steady state R_{ON} was monitored for different values of optical photon energy. The optically-induced deep level emission causes negative onsets in the steady state R_{ON} , which represent the activation energies of the deep-levels referred from the conduction band edge E_C . The R_{ON} step heights were used to estimate the sheet trap concentration n_T (cm^{-2}), using [11-16]:

$$n_T = (n_s)^2 \left[n_s - \frac{L_{dep}}{q\mu_n \Delta R_{ON}} \right]^{-1} \dots\dots\dots (3)$$

where L_{dep} is the lateral depletion of the 2DEG channel in the MISHEMT during the off-state high V_{DS} fill-pulse that for simpler HEMT structures is determined using an analytical model previously published by Arehart *et al.* [13]. Given that the MISHEMT devices used here have complex field plate geometries, and very high electric fields, this simple analytical model cannot be directly applied here. From Eqn (3) it is evident that for large values of ΔR_{ON} , n_T tends approximate n_s , irrespective of the value of L_{dep} . When the results are presented, it will be shown that the ΔR_{ON} is indeed large for the MISHEMTs studied here and therefore the impact of L_{dep} on estimated n_T is negligible because n_T approximates n_s for all values of L_{dep} .

The two terminal AlGaIn/GaN Schottky diode structures were investigated using constant capacitance deep level optical spectroscopy, CC-DLOS [24, 25] to evaluate deep levels without the presence of dielectrics and the complex high electric field distribution of the MISHEMT, so that vertical resolution of the deep trap distribution could be realized [24, 25]. In the CC-DLOS measurement, a 10 s fill pulse at 0 V was used to set the Schottky diode into accumulation. Following the fill pulse the Schottky device was

biased to a capacitance value of $\sim 11 \text{ nF/cm}^2$ (at Schottky gate voltage of roughly -4.7 V) which was maintained constant using a dynamic voltage control circuit. This constant capacitance condition ensures a total depletion of $\sim 700 \text{ nm}$ (i.e. much larger than the AlGaIn barrier thickness $\sim 30 \text{ nm}$), of which 670 nm depletion was into the GaN indicating that $\sim 96\%$ of the depletion region was in the GaN buffer. The sub-bandgap tunable optical excitation of the sample was performed using a monochromatic light source to enable detection of very deep traps in the system. The steady state voltage required to maintain a constant capacitance of $\sim 11 \text{ nF/cm}^2$ was recorded for different energies of incident light. The change in the voltage during the measurement corresponds to the change in charge due to charge emission from traps. Given that the GaN depletion used was $\sim 96\%$ of the total depletion, the CC-DLOS results mostly represent traps and other optical activity limited to the GaN buffer. The results will bear this out because even the AlGaIn bandgap cannot be detected for the CC-DLOS measurements of the Schottky structures, meaning the CC-DLOS detrapping response is emanating almost entirely from the GaN buffer traps. More details about CC-DLOS for studying bulk semiconductor states are in [25].

In addition to CC-DLOS the Schottky diodes were explored using surface potential based nanometer scale-DLOS methods to investigate traps physically located above the 2DEG (AlGaIn or surface traps) [26, 27]. This technique is a scanning probe microscope approach that enables measurements of light-induced local surface potential transient measurements with nm-scale spatial resolution [26, 27]. The scanning-DLOS experimental setup consists of a commercial Park XE-NSOM AFM system integrated with a custom built Xe-lamp based tunable sub-bandgap monochromatic light source.

The light from a 1000 W Xe lamp was spectrally resolved using a Cornerstone 260 monochromator and delivered to the sample through a custom fiber optics bundle. The biasing of the Schottky metal (with respect to the Ohmic terminal contacting the 2DEG) was achieved using a function generator. Custom designed electronics, software, and feedback techniques were adopted to optimize the time response of the measured surface potential transient V_{sp} . The localized surface potential transients of the Schottky diode under test were recorded between the Schottky metal and Ohmic contact of the test structures using switching conditions identical to those used in the CC-DLOS measurement. Spectrally resolved sub-bandgap monochromatic light over 1.2 eV to 4.3 eV was used to illuminate the structure while recording the steady state value of the surface potential transients thus resulting in scanning-DLOS spectra.

3. Results and Discussion

Figure 1 shows the on-resistance transients recorded for different off-state high V_{DS} conditions. The results indicate that there is no significant increase in the on-resistance 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. A possible mechanism describing this slow R_{ON} recovery process will be presented later in this paper. Figure 2 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 (threshold voltage) - shifts

because very little V_T change (<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, 17] the drain-to-gate capacitance was measured with the $V_{GS} < V_T$ versus V_{DS} . With increasing V_{DS} , the channel under the field plates begin to deplete. If the V_{DS} is large enough to deplete all the 2DEG electrons under a given field plate, an increased effective separation between the gate and drain occurs results in a sudden drop or step in C_{GD} . Multiple such steps were detected in the C_{GD} where each step corresponds to a field plate [2], [17]. For voltages exceeding $V_{DS} = 200$ V and beyond, no more steps were observed in the three terminal high voltage $C_{GD} - V_{DS}$ characteristics indicating that the lateral depletion in the device has extended beyond the longest field plate. These results suggest that the peak electric field was at the edge of last field plate for $V_{DS} > 200$ V which means that the onset in Fig. 2 is due to the electron trapping occurs primarily at the edge of the longest field plate. The strong dependence of the R_{ON} signal to the off-state V_{DS} is indicative of a virtual-gating process similar to what has been reported previously in RF GaN HEMTs at lower voltage switching conditions [12, 13]. The R_{ON} recovery as a function of time suggests electron emission from the traps that allows the local 2DEG and therefore the R_{ON} to recover as a function of time.

The R_{ON} transient measurements at room temperature were recorded for different baseplate temperatures to explore the temperature dependence of the transient time constants to possibly identify any activation energies of the traps involved. Figure 3 shows this data collected for a given off-state V_{DS} switched from 250 V. Interestingly at

low temperatures, little R_{ON} degradation was observed. To examine the time constants of these transients, isothermal DLTS analysis of the transients was performed. For a given temperature, the negative peaks in the isothermal CI_D -DLTS data represents the characteristic time-constant of the transient at that temperature. The Arrhenius plot extracted from this data is plotted in Fig. 4(b) reveals a thermal activation energy of 0.02 eV and a non-physically small thermal capture cross-section of $1 \times 10^{-28} \text{ cm}^2$. The Arrhenius data of a typical thermally activated trap (for example, E_C -0.57 eV level) from previous works[12–14] is plotted as example to contrast against the Arrhenius data from the R_{ON} recovery transients shown in Fig. 4(b). Typical thermally activated traps (such as the E_C -0.57 eV) have their characteristic electron emission time constant vary by at least 3 orders of magnitude over $\sim 100 \text{ K}$ temperature change. However the trap(s) associated with the R_{ON} transients, in this work, shows no evidence of a typical thermal process. If the R_{ON} recovery process in these MISHEMTs were truly thermally activated, then change of baseplate temperature would change the characteristic emission time constant by several orders of magnitude over the given temperature range. However as it is shown in Fig. 4(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. Later in this paper, we propose a model describing why the emission of the traps possibly follows this non-thermally activated process in the MISHEMTs.

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 CI_D -DLOS). The results of the optical spectroscopy on the MISHEMT are shown in Fig. 5. In the MISHEMT, the R_{ON} after off-

state $V_{DS} = 250$ V application is persistently high at ~ 150 Ω -mm and is independent of light with energy < 2 eV. This high on-resistance state of the MISHEMT caused by severe drain-access region electron trapping affecting the local 2DEG is shown in Fig. 6(a). For incident DLOS light energies > 2 eV, photoionization of a $\sim E_C - 2$ eV trap recovers the entire R_{ON} and this recovered state is captured in Fig. 6(b). This large ΔR_{ON} amplitude can be used to estimate a (sheet) trap density using the Eqn. 3. The estimated trap density n_T is very large (between 9.8×10^{12} cm^{-2} and 1×10^{13} cm^{-2}) and almost approaches n_s for assumed values of L_{dep} ranging from as large as 10 μm to as small as 1 nm. As was previously discussed, this apparent insensitivity of estimated n_T to L_{dep} is due to the large measured ΔR_{ON} value used as input to Eqn (3).

With the $E_C - 2.0$ eV activation energy of the dominant trap associated with the R_{ON} degradation identified, the concentration of this defect and its physical location are now explored. In the transistor with its intricate geometry and complex vertical and lateral electric fields at high voltages, it is difficult to distinguish whether the trapped charge occurs above or below the 2DEG, similar to previous reports [17]. To mitigate this, CC-DLOS and scanning-DLOS methods were applied to the two-terminal AlGaIn/GaN Schottky diodes for which lateral fields and transistor design issues are not present, so that complementary “materials-based” measurements could be made to augment the HEMT-based characterization results, as described next.

As seen in Fig. 7, the CC-DLOS results of the AlGaIn/GaN Schottky diode shows a negative onset at $\sim E_C - 2$ eV that matches the $\sim E_C - 2$ eV trap signature detected using CI_D -DLOS in the MISHEMT (shown in the same figure for convenience). Furthermore, the CC-DLOS onset at $E_C - 3.28$ eV is characteristic of a much-studied level in n-GaN

that has been attributed to residual carbon impurities [21, 28, 29], and serves as a marker that the CC-DLOS spectrum is dominated by levels in the GaN buffer. This is further supported by the fact that there is no evidence of any feature associated with the AlGaN bandedge (only the GaN bandedge is seen) or any other state between ~ 3.7 eV–4 eV that have been previously [21, 30] associated with AlGaN levels in CC-DLOS spectra. These observations combined with the fact that there is also no dielectric layer present in these Schottky test structures, provides strong indication that the $\sim E_C - 2$ eV level resides within the GaN buffer, and by corollary, is therefore unrelated to the AlGaN, its surface or its interface with GaN.

Direct evidence that the $E_C - 2.0$ eV trap is located in the GaN buffer demonstrated by the application of scanning-DLOS measurements that were performed in the openings between the Schottky gate and the Ohmic contact where the AlGaN surface was exposed as shown in Fig. 8. The figure 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 and therefore screens any charge below the 2DEG making the measurement sensitive only to traps above the 2DEG in the AlGaN barrier [26, 27]. Figure 9 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. The noteworthy point here is 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 and the GaN bandgap observed earlier in the CC-DLOS data (Fig. 7). Instead, only AlGaN-related features were observed, namely an $E_C - 3.7$ eV trap that

has been reported previously [21] and the AlGa_N bandedge near 4 eV. This result provides further confirmation that the E_C-2 eV trap is only present in the GaN buffer.

With the experimental evidence described, which shows the $E_C - 2$ eV trap that causes current collapse at high voltage switching appears to be a buffer trap, we now consider the physical process for the current collapse through this trap using a simple analytical model. The bulk concentration of the E_C-2 eV trap necessary to completely pinch-off the MISHEMT was estimated using simple calculations. If for the sake of argument it is assumed that the E_C-2 eV traps are uniformly distributed over 3 μm of the GaN buffer, then $1 \times 10^{13} \text{ cm}^{-2}$ sheet concentration corresponds to $\sim 3 \times 10^{16} \text{ cm}^{-3}$ bulk concentration. This is a reasonable value because the E_C-2 eV trap has been previously detected in bulk GaN within bulk concentrations up to $1.4 \times 10^{16} \text{ cm}^{-3}$ [28]. On the other hand, if the E_C-2 eV trap were assumed to be contained within the 30 nm thick AlGa_N barrier, the corresponding required bulk concentration of this trap in the AlGa_N barrier would be $\sim 3 \times 10^{18} \text{ cm}^{-3}$. This very high estimate is unreasonable because of two reasons. First, close examination of previous reports on DLOS studies in bulk AlGa_N have not revealed an E_C-2 eV trap in bulk AlGa_N [30]. Secondly, the estimated bulk concentration of the E_C-2 eV trap is 10X larger than the *total* concentration of all traps previously reported in bulk AlGa_N [30]. It is therefore very unlikely that this E_C-2 eV trap could occur especially in such high concentrations in the AlGa_N film of the transistors and diodes under study.

It is now quite clear that the E_C-2 eV defect is located in the GaN buffer. Given that this level was detected in the Schottky diode test structures where no high voltage electric stressing was applied to have formed this defect in any localized fashion, this trap

was likely to be present uniformly in the buffer layer, both under the gate and in the access 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 electric fields that peak at the field plate edges in the structures during the application of high off state V_{DS} ($>200V$). It is therefore the combination of the uniform presence of this pre-existing E_C-2eV trap in large bulk concentrations ($\sim 3 \times 10^{16} \text{ cm}^{-3}$) 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 this trap causes current collapse, a simple physical model is proposed that accounts for the filling and emptying of this trap (i.e. its modulation) under high off-state V_{DS} , in spite of its deep position in the bandgap and semi-insulating nature of the buffer layer. Figure 10 represents our proposed model. The energy band diagrams plotted as Figs 10(b) and 10(c) represent those extracted along a vertical cutline yy' [shown in Fig. 10(a)] taken just beyond the longest field plate. Before application of any high voltage in equilibrium conditions, the occupancy of the 2 eV trap in the GaN buffer is shown in Fig. 10(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 closer to the AlGaN/GaN interface are filled with electrons and therefore ionized. The occurrence of filled $E_C-2 \text{ eV}$ traps before application of any high voltage is validated by the CC-DLOS results in shown in Fig.7. The detection of $E_C-2 \text{ eV}$ 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 $E_C-2 \text{ eV}$ signature in the Schottky diodes. What was detected in the CC-DLOS measurements is simply the small fraction of the filled or

ionized $E_C-2\text{eV}$ traps near the AlGaIn/GaN interface that remains filled by virtue of its location below the Fermi level at $V_{GS}=0\text{V}$ in the dark. These previously filled $E_C-2\text{ eV}$ levels detrapp on the application reverse bias and in the presence of light with photon energy $h\nu > 2\text{ eV}$. During the fill pulse, however, these same traps close to the AlGaIn/GaN interface get refilled on the application of $V_{GS}=0\text{V}$ fill pulse for 10s thereby restoring the device. However in the MISHEMT, for this level to have a massive impact on the transistor terminal characteristics, it is essential that a large number of traps including ones far into the buffer also participate. Their participation is enabled by the application of high electric field during the high off-state V_{DS} switching.

During the application of high off-state $V_{DS} (> 200\text{V})$, the very high electric fields localized at the edge of the field plates can cause massive localized electron injection in the $E_C-2\text{ eV}$ trap deep into the GaN buffer through mechanisms such as Zener tunneling, hot carrier injection, reverse gate leakage among several others [17, 18]. With the traps now filled with electrons, the energy band diagrams of the transistor soon after the high voltage fill pulse are as shown in Fig. 10(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 R_{ON} effect. The transistor recovers from this state and reverts back to state represented in Fig. 10(b) when exposed to light with photon energies $>2\text{ eV}$ that emit trapped electrons. Figure 11 shows the energy band-diagrams of the HEMT along a horizontal cutline presented before and after the high voltage application. Fig. 11(a) shows that the cutline is obtained in deep the GaN buffer. In equilibrium conditions shown in Fig. 11(b), the $E_C-2\text{ eV}$ trap remains free of electrons because it lies above the Fermi level this deep in the GaN buffer. In Fig. 11(c) the non-equilibrium energy band

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 high degree of 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 recovery is possible because of discharging of the E_C-2 eV trap through a non-thermally assisted process akin to a tunneling mechanism. The shape of this band diagrams shown in Fig. 11(c) soon after the high voltage off-state fill pulse provides an explanation for how such very deep E_C-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. Similar observations and models were also presented by Jin et al. in [17].

5. Conclusion

In conclusion, spatially sensitive optical and thermal trap spectroscopies were applied to GaN/Si MISHEMTs. A deep $\sim E_C-2$ eV electron trap was shown to be responsible for the observed R_{ON} degradation of the device that occurs soon after high voltage (>200 V) switching. This trap is activated at the edge of the field plate on application of high voltages (>200 V) and shows characteristics similar to that of previously detected virtual-gate traps [12]-[13]. 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_{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 control of 2DEG density to reduce fields without compromising performance.

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Figure 1 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 tend to recover to steady state R_{ON} case at very long times ($> 10^4$ seconds).

Figure 2 On-resistance sampled at 1 s after switching the MISHEMT as discussed in Fig. 1 for different off-state drain voltages. A sharp onset at 200 V indicates that significant on-resistance increases take place only after the threshold electric field is exceeded at the edge of the longest field plate where the electron trapping occurs.

Figure 3 On-resistance transients recorded for off-state $V_{DS}=250$ V 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 give temperature is obtained using iso-thermal DLTS analysis of these transients shown in the Fig. 4(a).

Figure 4 (a) Iso-thermal CLD -DLTS analysis of R_{ON} transients reveal characteristic time-constant of the respective transients for that given temperature. The time-constant of the transient features observed is mostly independent of temperature unlike a traditional thermally activated trap. This fact is illustrated from the Arrhenius plot shown in 4(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 and very different from the Arrhenius data of a thermally detected traditional $E_C=0.57$ eV trap. These results reveal that the R_{ON} recovery phenomenon here is not a typical thermally activated process.

Figure 5 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 $< 2\text{ eV}$ the on-resistance remained persistently high ($\sim 150\text{ Ohm-mm}$) soon after switching from off-state $V_{DS} = 250\text{ V}$ case. The application of light energies $> 2\text{ eV}$ recovers the on-resistance to the original steady state values $\sim 30\text{ Ohm-mm}$. The sharp negative onset at 2 eV informs us of an $E_C - 2\text{ eV}$ electron trap directly linked to this R_{ON} degradation effect.

Figure 6 Schematic cross-sections of the MISHEMT showing the charge state of the $E_C - 2\text{ eV}$ trap (a) soon after high off-state V_{DS} switching in the dark and (b) after shining light energies $> 2\text{ eV}$. The high voltage induces trapping of electrons in the $E_C - 2\text{ eV}$ 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 $E_C - 2\text{ eV}$ 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 original steady state values before application of any high off-state V_{DS} .

Figure 7 CC-DLOS results from the AlGaN/GaN Schottky diode switched compared against CI_D -DLOS from the MISHEMT. Both the MISHEMT and the diode show the same $E_C - 2$ eV trap feature which proves that this feature is unrelated to the dielectric in the MISHEMT. Also, the CC-DLOS from the Schottky diode reveals the $E_C - 3.28$ eV trap, a well known GaN defect in addition to the GaN bandedge. The absence of tell-tale AlGaN features in the Schottky diode CC-DLOS spectra is not surprising given that this measurement was performed with the depletion in the GaN being $\sim 96\%$ of the total depletion.

Figure 8 Schematic showing the nano-scale vertical and lateral sensitivity of the AFM probe tip used in the scanning-DLOS measurements.

Figure 9 Nano-scale DLOS data sensitive to AlGaIn surface potential transients reveal no sign of the E_C-2 eV trap despite switching the Schottky diode in the same scheme as the CC-DLOS. An $E_C-3.7$ eV AlGaIn trap signature and the AlGaIn bandedge were detected in the surface potential spectra underscoring the ability to this technique to monitor traps exclusively in the AlGaIn film.

Figure 10 (a) Shows schematic cross-section of the HEMT and a vertical cutline $y-y'$ 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 11 (a) Shows 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 $E_C - 2 \text{ eV}$ 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.