Impact of the Al Mole Fraction in the Bulk- and Surface-State Induced Instability of AlGaN/GaN HEMTs

S. DasGupta[1], M. Sun[2], A. Armstrong[1], R. Kaplar[1], M. Marinella[1], J. Stanley[1], M. Smith[1], S. Atcitty[1] and T. Palacios[2]
[1]Sandia National Laboratories, Albuquerque, NM 87185 USA
[2] Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

ABSTRACT

Charge trapping and slow (10 s to > 1000 s) detrapping in AlGaN/GaN HEMTs designed for high breakdown voltage (> 1500 V) are studied to identify the impact of Al molefraction and passivation on trapping. Two different trapping components, TG1 (E_a = 0.62 eV) and TG2 (with negligible temperature dependence) in AlGaN dominate under gate bias stress in the off-state. $Al_{0.15}Ga_{0.85}N$ shows much more vulnerability to trapping under gate stress in the absence of passivation than does AlGaN with a higher Al mole fraction. Under large drain bias, trapping is dominated by a much deeper trap TD. Detrapping under illumination by monochromatic light shows TD to have $E_a \approx 1.65$ eV in $Al_{0.26}Ga_{0.74}N$ and $E_a \approx 1.85$ eV in $Al_{0.15}Ga_{0.85}N$. This is consistent with a transition from a deep state (E_c - 2.0 eV) in the AlGaN barrier to the 2DEG.

INTRODUCTION

AlGaN/GaN High-Electron-Mobility Transistors (HEMTs) have traditionally been the device of choice in RF electronics. More recently, the ease of achieving a low on-state resistance due to high channel mobility (μ_{ch}) coupled with a wide bandgap (E_g = 3.4 eV) has led to significant advancements in developing the GaN HEMT as a device for the next generation of high voltage power electronics [1-2]. While greatly detailed studies of defects in the AlGaN/GaN system exist, much of the focus in HEMTs has been on specific kinds of trapping that limit RF performance, such as traps causing gate lag. In studies analyzing the effects of high DC gate or drain voltage stress (including permanent degradation) the traps that have been studied in great detail have short detrapping time constants (< 1 s at room temperature) [3-4]. In spite of evidence of trapping that shows much slower (10 s to > 1000 s) detrapping behavior in most stress experiments, relatively few studies analyzing traps causing this kind of behavior exist [5-6].

In this work, we investigate the effects of different bias conditions on the detrapping rate in AlGaN/GaN HEMTs. Traps with room-temperature time constants ranging from 10 to 1000 s were characterized thermally using the current transient method, and deeper traps were characterized optically using sub-bandgap monochromatic light. The effect of passivation on individual trapping components was analyzed for different mole fractions of Al in AlGaN.

DEVICE DETAILS

Four different sets of devices were fabricated at MIT on silicon (111) substrates for two different breakdown voltage ranges. One set of devices were fabricated to achieve a maximum breakdown voltage of 500 V. These used $Al_{0.26}Ga_{0.74}N$ in the barrier and had a threshold voltage

(V_{th}) of approximately -1.8 V. The other set of devices were designed to achieve a maximum breakdown voltage of 1800 V. In order to reduce the two dimensional electron gas (2DEG) density (and hence increase breakdown voltage), these devices used $Al_{0.15}Ga_{0.85}N$ in the barrier and had a threshold voltage (V_{th}) of approximately -3.6 V. Each set of devices ($Al_{0.15}Ga_{0.85}N$/GaN and $Al_{0.26}Ga_{0.74}N$/GaN) were fabricated both with and without surface passivation (an $Al_2O_3/SiO_2/Al_2O_3$ stack deposited by atomic layer deposition).

DETRAPPING BEHAVIOR UNDER GATE AND DRAIN BIAS STRESS

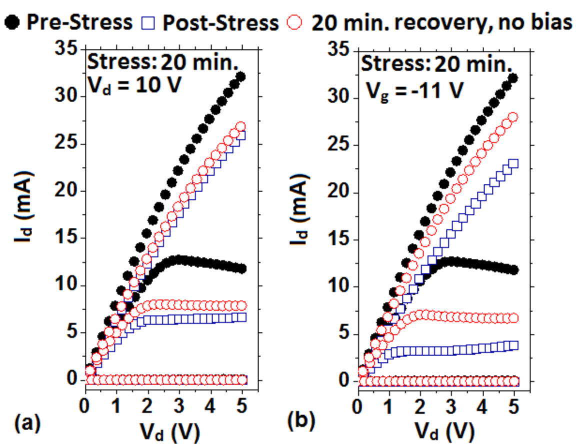

Fig. 1. I_d–V_d characteristics of a passivated $Al_{0.15}Ga_{0.85}N$/GaN HEMT for V_{gs} = -5 to 1 V, in steps of 3 V. (a) Drain stress (V_{ds} = 10 V, V_{gs} = 0 for 20 min) results in almost no recovery 20 min. after withdrawal of stress. (b) Significant recovery is seen 20 min. after withdrawal of gate stress (V_{gs} = -11 V, V_{ds} = 0 for 20 min).

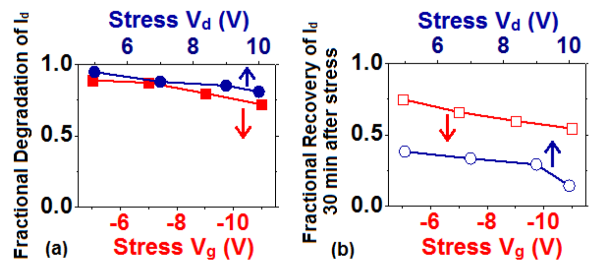

Fig. 2. (a) Fractional degradation in current, for different conditions on the gate stress (red) and drain stress (blue) of the device in Fig. 1. Stress duration = 20 min. (b) For comparable degradation in the overall drain current, the fractional recovery in 30 min. is much higher for gate stress than for drain stress. All I_d measurements are done at V_{gs} = 1V, V_{ds} = 5V.

The most important observation in our experiments is that a high on-state drain voltage stress leads to much slower detrapping compared to a high off-state gate voltage stress for all of the devices studied. Fig. 1 shows the I_d–V_d characteristics of a passivated $Al_{0.15}Ga_{0.85}N$/GaN HEMT (L_g = 2 µm, W_g = 100 µm, L_{ds} = 10 µm, V_{th} = -3.6 V). Three measurements were performed: pre-stress, immediately post-stress, and after the device had recovered for 20 min. at room temperature. Drain stress (V_{ds} = 10 V, V_{gs} = 0 for 20 min.) results in almost no recovery 20 min. after withdrawal of stress, whereas significant recovery is seen 20 min. after withdrawal of gate stress (V_{gs} = -11 V, V_{ds} = 0 for 20 min). It is very important to perform the trapping and thermal detrapping experiments in complete darkness. Much of the trapping is absent, and the detrapping is much faster even in the presence of ambient light. Fig. 2 summarizes the fractional loss in drain current and the fractional recovery for the $Al_{0.15}Ga_{0.85}N$/GaN HEMT shown in Fig. 1 for a range of biases. At V_{gs} = 1 V, V_{ds} = 5 V, we define $I_{d,post\text{-}stress}$ as the current measured right after withdrawal of the stress (there is a ~ 1 s delay between the withdrawal of stress and the start of the I_d–V_d measurement). $I_{d,post\text{-}recovery}$ is measured 30 min. after recording $I_{d,post\text{-}stress}$. The fractional recovery is defined as the ratio ($I_{d,post\text{-}recovery}$ - $I_{d,post\text{-}stress}$)/($I_{d,pre\text{-}stress}$ - $I_{d,post\text{-}rtress}$) at V_{gs} = 1 V, V_{ds} = 5 V. After recording $I_{d,post\text{-}recovery}$, the microscope lamp was turned on and the device recovered to its pre-stress current before the start of the next bias measurement. For the entire range of biases, the recovery from a drain bias stress is significantly lower than that from a gate bias stress.

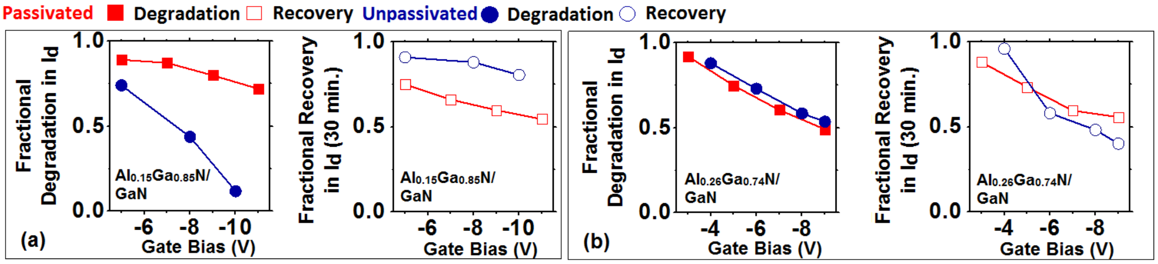

Fig. 3. Comparison of gate bias-induced degradation and recovery in equally sized, designed, and fabricated (a) $Al_{0.15}Ga_{0.85}N$/GaN and (b) $Al_{0.26}Ga_{0.74}N$/GaN HEMTs with and without passivation. $Al_{0.15}Ga_{0.85}N$/GaN shows a large increase in trapping in absence of passivation.

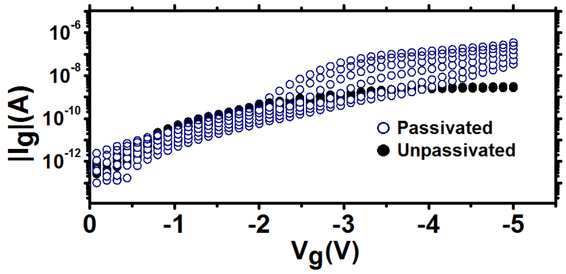

Fig. 4. $|I_g|$-V_{gs} plots of two $Al_{0.15}Ga_{0.85}N$/GaN HEMTs (L_g = 2 µm, W_g = 100 µm, L_{ds} = 40µm) for V_{ds} = 0 to 5 V, in steps of 1 V. One device is passivated, the other unpassivated. Gate current increases post-passivation.

A similarly fabricated and designed unpassivated HEMT shows very large loss of current (Fig. 3a) from the gate stress. This is not the case with (Fig. 3b) $Al_{0.26}Ga_{0.74}N$/GaN devices. Most of the lost current is recovered within the 30 min. time period, showing the increase in trapping to be due to the faster trapping component (we shall refer to this as TG) dominating during gate stress. Also, this study for the drain stress, where the slower component (we shall refer to this as TD) dominates shows almost no difference between passivated and unpassivated devices (Fig. 3b). While the passivation scheme chosen here is very effective in reducing the instability in drain current, it also significantly increases the gate current (Fig. 4), probably due to an increase in the electric field. A better gate dielectric is therefore necessary to reduce gate leakage in passivated $Al_{0.15}Ga_{0.85}N$ devices.

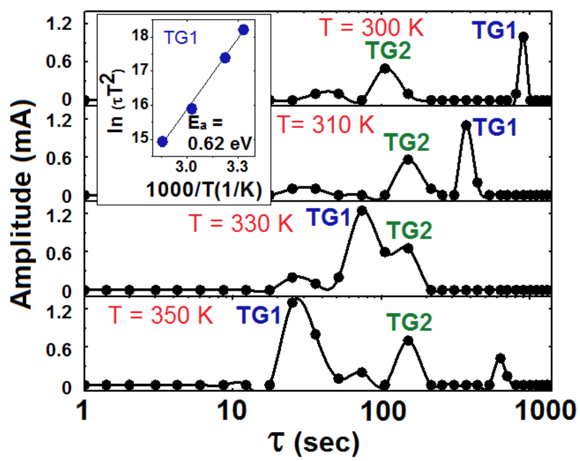

Fig. 5. Extracted time constant spectra and E_a (inset) for a passivated $Al_{0.15}Ga_{0.85}N$/GaN HEMT (L_g = 2 µm, W_g = 100 µm, µm, V_{th} = -3.6 V) at V_{ds} = 1 V, V_{gs} = 0 following stress at V_{gs} = -7 V, V_{ds} = 0 as a function of temperature.

DEFECT CHARACTERIZATION USING THERMAL DETRAPPING TRANSIENTS

The current transient methodology (described in [7]) was used to characterize the trapping components. The stress voltage was applied for 20 min., following which the detrapping transient was recorded at V_{ds} = 1 V, V_{gs} = 0. In the current transient method, the detrapping transient data $\Delta I_d(t)$ (defined as $I_d(t)$ - $I_d(0)$, where $I_d(0)$ is the current at the first recorded instant of detrapping) is analyzed by fitting to a sum of pure exponentials in a least-mean-square fashion. Transients of a passivated $Al_{0.15}Ga_{0.85}N$/GaN HEMT (L_g = 2 µm, W_g = 100 µm, L_{ds} = 10 µm, V_{th} = -3.6 V) at V_{ds} = 1 V, V_{gs} = 0 following stress at V_{gs} = -7 V, V_{ds} = 0 were analyzed to extract the time constant spectra at various temperatures (Fig. 5). The gate stress at room temperature produced two clear detrapping peaks, which we shall refer to as TG1 (at τ ≈ 800 s) and TG2 (at τ ≈ 150 s). While TG1 shows clear temperature dependence E_a(TG1) = 0.62 eV (Fig. 5 inset), TG2 stays practically fixed over the temperature range measured (300 K – 350 K).

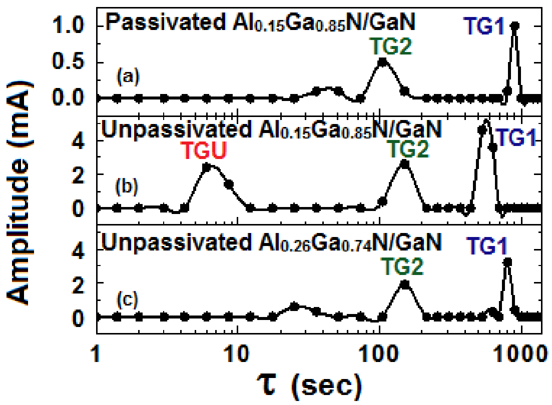

Fig. 6. Extracted time constant spectra for three equally sized, designed, and fabricated (a and b) $Al_{0.15}Ga_{0.85}N$/GaN HEMTs with and without passivation and c) $Al_{0.26}Ga_{0.74}N$/GaN HEMT without passivation at room temperature.

Since unpassivated $Al_{0.15}Ga_{0.85}N$/GaN HEMTs showed the greatest vulnerability to charge trapping under gate stress, the detrapping time constant spectrum was extracted and compared to that of an equally sized, designed, and fabricated HEMT with passivation (Fig. 6a and 6b). The unpassivated samples show an increase in both TG1 and TG2 amplitudes. In addition, a third peak that we refer to as TGU appears at approximately 6 s. The appearance of TGU is specific to the low Al mole fraction unpassivated device. Figs. 6b and 6c show a comparison of similar detrapping time constant spectra of two equally sized, unpassivated devices, one $Al_{0.15}Ga_{0.85}N$/GaN and one $Al_{0.26}Ga_{0.74}N$/GaN. TGU appears only in the $Al_{0.15}Ga_{0.85}N$/GaN device.

CHARACTERIZATION OF DEEP LEVELS (TD) THROUGH OPTICAL DETRAPPING

Since the thermal transients following a high drain bias take an excessively long time to detrap the majority of the trapped charge at room temperature, we used monochromatic light to analyze the detrapping following stress. The devices were stressed with a high bias on the drain with V_{gs} = 0 for 20 min. After this, the detrapping behavior was studied under illumination of monochromatic light with energy being swept from 1.20 - 2.50 eV at V_{ds} = 1 V, V_{gs} = 0. The optical exposure time for each energy was about 7s and there was a 9s interval between exposure to two consecutive energies. Light from a broadband Xe source was dispersed using a ¼ m monochromator with appropriate mode-sorting filters to achieve 0.05 eV resolution at an average photon flux of ~2-10×10^{16} $cm^{-2}s^{-1}$. Fig. 7(a) shows the transient following an exposure of 1.2 eV light on a passivated $Al_{0.15}Ga_{0.85}N$/GaN HEMT following a 20 min. stress at V_{ds} = 8 V, V_{gs} = 0. The shutter opened at t ≈ 1.3 s exposing the device to light. There is no visible change in the detrapping time constant before (thermal) and after (thermal and optical) 1.3 s, indicating that there are no significant optical detrapping processes with energies lower than 1.2 eV. This also shows that TG1 and TG2 have small optical cross-sections for 1.2 eV light, since these traps are populated and thermally detrapping. For comparison, the transient with 1.85 eV light in Fig. 7(b) shows a sharp change in drain current following the exposure at 1.3 s. Fig. 7(c) shows the current at the end of each 7s optical exposure. An inflection point indicates a strong resonance of the monochromatic light with the trap, resulting in electron photoemission. This inflection happens near 1.85 eV for the $Al_{0.15}Ga_{0.85}N$/GaN sample. For higher energies there is no further inflection until the current surpasses the pre-stress value. This strongly suggests that the 1.85 eV trap is the major component of TD. Fig 7(d) shows similar results following the same experiment on a passivated $Al_{0.26}Ga_{0.74}N$/GaN HEMT. While the profile follows the same trends, the inflection point is now near 1.65eV.

Interestingly, the defect level appears to become shallower by about 0.2 eV relative to the conduction band (E_c) going from $Al_{0.15}Ga_{0.85}N$ to $Al_{0.26}Ga_{0.74}N$. Defects in bulk AlGaN have been typically shown to track one of the band edges [8-9] or the vacuum level. For E_a(TD) to become shallower with increasing AlN mole fraction, the defect level cannot track E_c or the vacuum level. For E_a(TD) to track E_v and become 0.2 eV shallower relative to the conduction band going from $Al_{0.15}Ga_{0.85}N$ to $Al_{0.26}Ga_{0.74}N$, the electron affinity χ(GaN) has to be approximately 1.5 eV (assuming χ(AlN) = 0.6 eV). The $\Delta E_c/\Delta E_v$ in such a situation would be approximately 0.5. While conflicting opinions exist about the value of χ(GaN) and χ(AlN) [10], all studies report $\Delta E_c/\Delta E_v > 1$ and very often ~2. Thus, the change in E_a(TD) with AlN mole fraction can be better explained by a tunneling-assisted optical transition from a defect state tracking the AlGaN band edge to the GaN 2DEG.

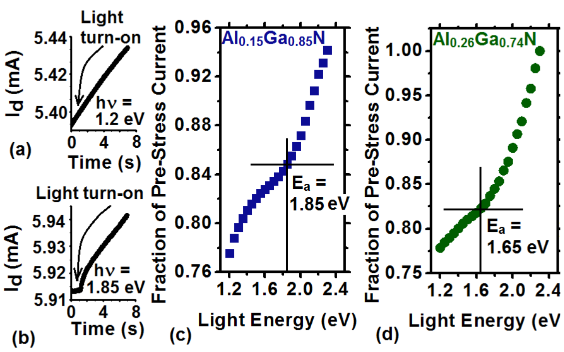

Fig. 7. (a) Current transient at V_{ds} = 1 V, V_{gs} = 0 from exposure to 1.2 eV and (b) 1.85 eV light on a passivated $Al_{0.15}Ga_{0.85}N$/GaN HEMT, following 20 min stress at V_{ds} = 8 V, V_{gs} = 0. The device is exposed to light at t ≈ 1.3 s. (c) Fraction of pre-stress current at the end of a 7 s optical exposure for an $Al_{0.15}Ga_{0.85}N$/GaN HEMT and a (d) $Al_{0.26}Ga_{0.74}N$/GaN HEMT over a range of photon energies.

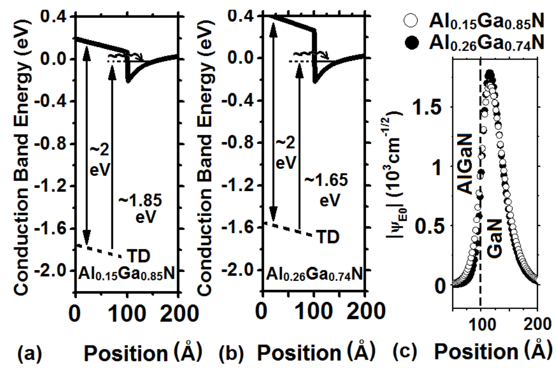

Fig. 8. Simulated E_c and E_0 in the channel 2DEG (E_0) for (a) the $Al_{0.15}Ga_{0.85}N$/GaN and (b) $Al_{0.26}Ga_{0.74}N$/GaN devices, near the heterointerface. (c) Simulated E_0 wavefunctions show significant tails in the AlGaN, resulting in near-interface AlGaN levels delocalized in the plane of the 2DEG.

In power HEMTs, the relatively low molefraction AlGaN results in weak confinement of the wavefunction. Figs. 8(a) and (b) show simulated E_c and ground-state electronic levels in the channel (E_0) for the $Al_{0.15}Ga_{0.85}N$/GaN and $Al_{0.26}Ga_{0.74}N$/GaN devices. For a level TD tracking the AlGaN E_c near E_c – 2.0 eV, an optical excitation from TD to the GaN 2DEG is possible without excitation to the AlGaN E_c first. As Fig. 8(c) shows, a prominent tail of the E_0 wavefunction (ψ_{E0}) extends into the AlGaN over about 25 Å. This creates near-interface AlGaN states delocalized in the plane of the 2DEG. An optical excitation from TD to one of these states would result in a transition into the GaN 2DEG, due to the stronger localization of ψ_{E0} in GaN. For TD located at E_c – 2.0 eV, such a mechanism would result in E_a(TD) ≈ 1.85 and 1.65 eV in

$Al_{0.15}Ga_{0.85}N$/GaN and $Al_{0.26}Ga_{0.74}N$/GaN devices respectively, consistent with the experimental results. Such a defect has also been demonstrated previously in [11].

CONCLUSIONS

Slow detrapping in AlGaN/GaN HEMTs designed for high breakdown voltage is studied to identify the impact of Al mole fraction and passivation on trapping. Unpassivated and passivated $Al_{0.15}Ga_{0.85}N$/GaN and $Al_{0.26}Ga_{0.74}N$/GaN HEMTs are compared. The presence of ambient light strongly affects the trapping and detrapping rates. Trapping due to high drain bias stress in the on-state ($V_g = 0$) shows significantly slower recovery compared to trapping in the off-state. Two different trapping components, TG1 ($E_a = 0.62$ eV) and TG2 (having negligible temperature dependence) in AlGaN dominate under gate bias in the off-state. $Al_{0.15}Ga_{0.85}N$ shows much more vulnerability to the traps associated with TG1 and TG2 under gate stress in the absence of passivation than does $Al_{0.26}Ga_{0.74}N$. Under a large drain bias, trapping is dominated by a much deeper trap TD with $E_a \approx 1.65$ eV in $Al_{0.26}Ga_{0.74}N$ and $E_a \approx 1.85$ eV in $Al_{0.15}Ga_{0.85}N$. Recovery of TD under optical illumination is consistent with a transition from a defect approximately 2.0 eV below the AlGaN conduction band edge to the GaN 2DEG ground state.

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