UV-Assisted Probing of Deep-Level Interface Traps in GaN MISHEMTs and Their Role in Threshold Voltage & Gate Leakage Instabilities

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***Abstract*—This work demonstrates UV assisted probing of deep level traps in dielectric/GaN interface. The deep level donor traps lead to threshold voltage and gate leakage instabilities in GaN MISHEMTs. While UV exposure excites the deep traps, gate bias can sweep the trap energy state and trigger de-trapping. The recovery transient is evaluated to study the trap time constant. Besides, this work reveals a non-destructive technique to probe intrinsic traps as the UV exposure does not change the trap density across the device.**

***Index Terms*— Deep-Level Traps, Dielectric characterization, UV Assisted Trap Excitation, GaN HEMTs, Threshold Voltage Instability**

I. Introduction

Reliable GaN HEMT operation demands superior gate dielectric development as its bulk/interface traps can lead to threshold voltage (V_{TH}) instability, increased gate leakage (I_G) besides significantly affecting dynamic performance. A complete understanding of traps in the dielectric is hence essential for improving its reliability. While shallow traps are easily detectable by conventional techniques such as conductance method [1], photo-assisted C-V [2], DC and pulsed-mode I-V [3], it is more difficult to analyze deep traps as it is often difficult to activate them. However, such traps can easily get excited by the high electric field developed across the gate dielectric during sudden voltage spikes, a common phenomenon in power HEMTs. This necessitates an early detection of the deep level traps for reliable GaN HEMT operation. Moreover, presence of multiple interfaces in HEMTs result in inaccurate trap extraction by the conventional C-V techniques [4]. In this endeavor, a recent work by Yang et al. proposed a method of analyzing the second slope of C-V to evaluate traps in the device [5], where higher temperature and lower measurement frequency is imperative to detect deep level traps. However, such measurements are prone to noise and requires experimental setups with careful calibration to provide reliable results. In this work, we report a novel, easy to implement UV-assisted probing of deep level traps, which are a source of V_{TH} and I_G instabilities in GaN MISHEMTS.

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II. Device Fabrication and Experimentation

HEMTs were processed on MOCVD grown AlGaN/GaN on Si (Fig. 1), starting with Ti/Al/Ni/Au based ohmic contact formation. MESA isolation was then carried out using Cl_2 based dry etching. ALD grown 14 nm Al_2O_3+TiO_2 high-κ stack was then blanket deposited as gate oxide. Finally, 70 nm thick Ni/Au was deposited to form the gate electrode. The HEMT characteristics for $L_G = 5\ \mu m, L_{SD} = 23\ \mu m$ is depicted in Fig. 2. DC characterization of the HEMTs in dark and under/post UV was carried out at room temperature using Keithley 26XX SMUs and 42XX CVUs.

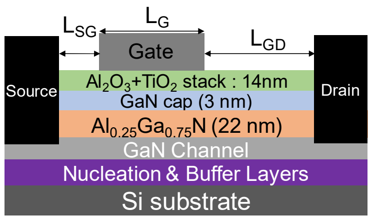

Figure 1. Cross-sectional view of AlGaN/ GaN HEMTs studied in this work.

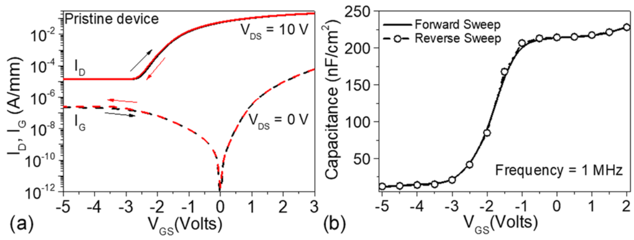

Figure 2. (a) Transfer characteristics,Gate leakage and (b) dual sweep C-V of pristine HEMT showing superior performance with negligible hysteresis, indicating excellent gate oxide/GaN interface quality.

III. Trap Excitation and Recovery

A. Trap Excitation by UV

Dual sweep I_D-V_{GS} and C-V characteristics of the pristine device, as shown in Fig. 2, depict negligible hysteresis and establish an excellent interface quality of gate oxide with GaN cap layer. However, a blanket exposure of device with 365nm UV light shifts the V_{TH} to left and introduces hysteresis (Fig. 3a). Further, UV exposure also significantly increases I_G (Fig. 3b). UV exposure ionizes deep level donor traps at the oxide/GaN interface (Fig. 4). This results in an increase in

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2DEG density at the AlGaN/GaN heterointerface, leading to a left shift in V_{TH}. The positively charged ionized deep donors also provide empty trap states for electrons to tunnel through the gate dielectric, which contributes to increased I_G.

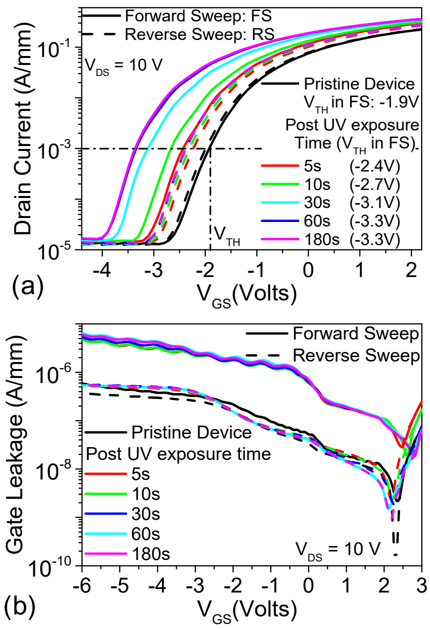

Figure 3. Dual sweep (a) I_D-V_{GS} charecteristics depicting negative shift in V_{TH} with increasing UV exposure time and (b) I_G-V_{GS} characteristics depicting increased I_G in forward sweep, due to excitation of (positively charged) deep donor traps.

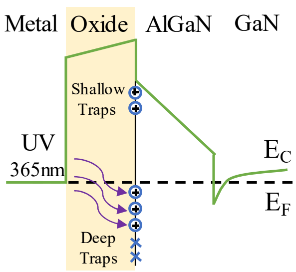

Figure 4. Schematic depicting excitation of deep-level traps at gate oxide/GaN interface by using UV.

B. Influence of UV Exposure Time

Fig. 3a shows that increase in UV exposure time leads to gradual negative shift in V_{TH}. The rate of V_{TH} shift however slows down above ~30s of UV exposure. In addition to this, I_G depicts an UV exposure time independent hysteresis besides a significant increase during forward sweep (Fig. 3b). I_G however, completely recovers to the level of pristine device in the reverse sweep. The rate at which I_G increases with UV exposure is higher than the rate of drain current or V_{TH} shift. This is attributed to exponential dependence of I_G on the tunneling probability, which increases after ionization of donor traps - allowing empty states for electron tunneling. Thus, I_G increase shows an exponential dependence on the ionized donor state density.

C. Time Dependent Recovery

Time dependent measurements were done post UV exposure to study the trap dynamics. Fig. 5 depicts ~ 2x increase in drain current (I_D) post UV exposure due to increase in 2DEG density after ionization of deep donor traps. Rate of increase in I_D too slows down post ~30s of UV exposure. Further, I_D does not recover to pristine level even after a relaxation period of 120s, indicating (i) deep level traps with time constants >120s to be associated with V_{TH} shift, or (ii) absence of carriers at the AlGaN conduction band edge to assist carrier de-trapping. Further I_D-V_{GS} in Fig. 6a shows minor recovery after a relaxation time of 600s. The I_G recovery (Fig. 6b) post different relaxation period shows four distinct regions with different recovery trends indicating deep level traps spread over a wide energy range being responsible for I_G increase. The V_{TH} recovery post reverse sweep is however relaxation time independent and does not recover to the pristine device level.

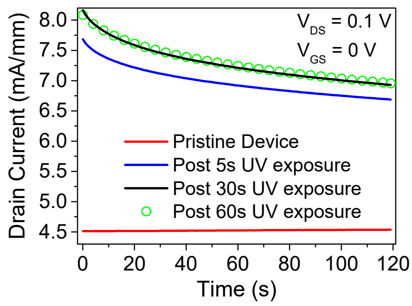

Figure 5. Dual sweep (a) I_D-V_{GS} charecteristics depicting negative shift in V_{TH} with increasing UV exposure time and (b) I_G-V_{GS} characteristics depicting increased I_G in forward sweep, due to excitation of (positively charged) deep donor traps.

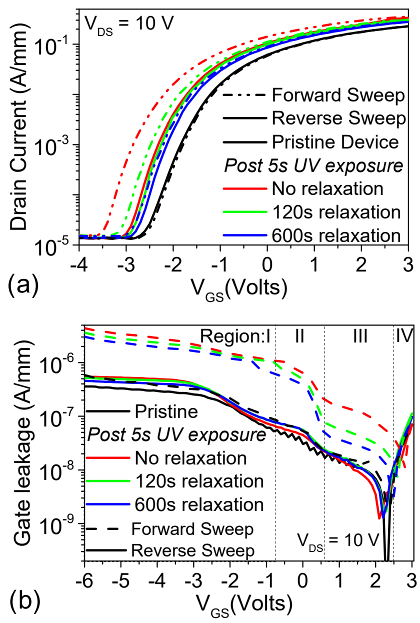

Figure 6. Post 5s UV exposure, (a) dual sweep I_D-V_{GS} characteristics, shows reduction in hysteresis and slow V_{TH} recovery, measured after increasing relaxation times. (b) I_G-V_{GS} charecteristics, measured after increasing relaxation times, exhibits four distinct regions. This shows different recovery trends with relaxation time indicating deep traps over a wide energy range to be responsible for gate leakage.

D. Bias Dependent Recovery

V_{TH} and I_G recovery during V_{GS} sweep indicates a bias accelerated de-trapping phenomena. Fig. 7a compares I_D-V_{GS} characteristics of a pristine device with device exposed to UV light for 5s. It shows that a second I_D-V_{GS} sweep immediately following the first sweep completely recovers the V_{TH} and I_G (Fig. 7b) irrespective of the relaxation time. Further, Fig. 8 depicts that the pristine device characteristics with no hysteresis are restored post two immediate I_D-V_{GS} dual sweeps with negligible relaxation time, implying a bias stimulated recovery phenomenon, which can be exploited to evaluate the trap states as follows.

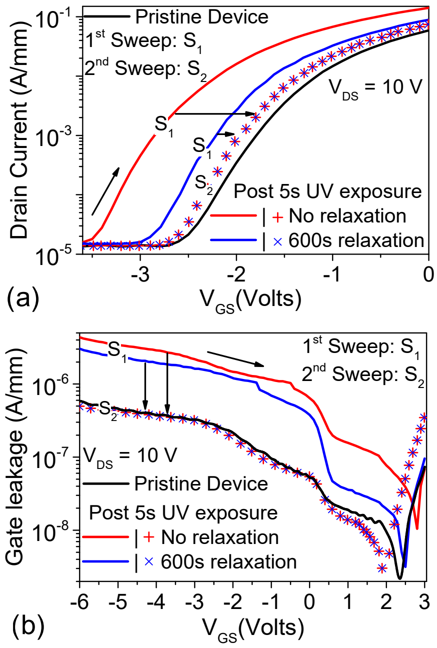

Figure 7. (a) I_D-V_{GS} and (b) I_G-V_{GS} characteristics of pristine device compared with the same post 5s UV exposure. It shows complete V_{TH} and I_G recovery by a second I_D-V_{GS} sweep immediately following the first sweep, irrespective of the relaxation time, implying a bias accelerated de-trapping phenomenon.

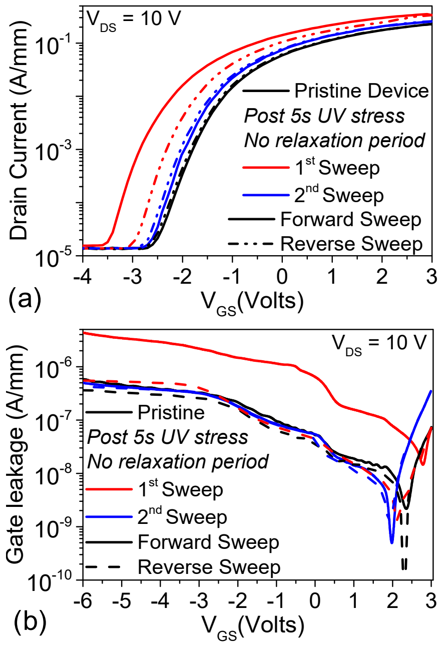

Figure 8. Post 5s UV exposure, two consecutive (a) I_D-V_{GS} and (b) I_G-V_{GS} sweeps carried out without any relaxation period. V_{TH} and I_G recovers to pristine level following the two sweeps even without any relaxation post UV exposure.

E. Trap Detection by UV

Fig. 9 shows % increase in I_D and I_G when subjected to 1s UV exposure under different V_{GS}. The figure indicates that while UV assisted trap excitation cannot be controlled, their relaxation can be effectively controlled by varying V_{GS}. V_{TH} and I_G dependence on UV exposure and its bias dependent recovery can be explained by considering the trap dynamics as follows: Decreasing V_{GS} will effectively result in an increase in the Fermi energy (E_F) (Fig. 10). This would provide electrons to recombine with the positively charged ionized donor traps thereby neutralizing them and lead to recovery of V_{TH} (I_D reduction) and I_G. Fig. 9 shows the time to recover reduces drastically as V_{GS} is made more negative. This indicates detection of shallower traps which have faster recovery. Hence,

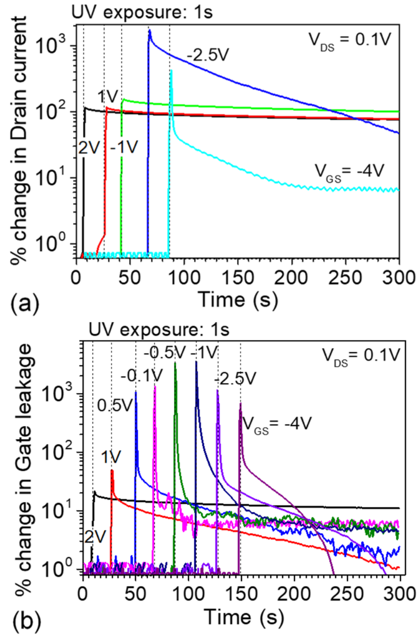

Figure 9. (a) I_D and (b) I_G measured with time for different V_{GS} post 1s of UV exposure. Sweeping V_{GS} towards negative initiates the recovery process due to trap deionization by electron injection. Faster recovery time with negative V_{GS} shift indicates detection of shallower traps (V_{DS} = 0.1V to negate V_{DS} induced recovery).

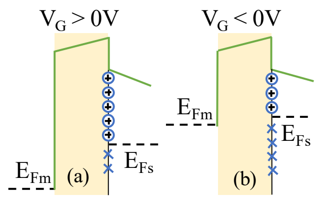

Figure 10. Schematic band diagram of metal/oxide/AlGaN stack under (a) positive V_{GS} and (b) negative V_{GS} showing gate bias as a control parameter to scan the trap energy levels. Negative V_{GS} shifts Fermi energy upwards, providing electrons to deionize positively charged donor traps inducing V_{TH} and I_G recovery.

V_{GS} can be used to control de-ionization of traps located at different energy levels, enabling detection of trap energy level. The recovery transient can be evaluated to extract the trap relaxation time constant associated with the trap states. Carrier injection and subsequent de-trapping can be enhanced by increasing V_{DS}. The drain electric field accelerates V_{TH} recovery besides resulting in a complete I_G recovery (Fig. 11). The % change in I_D is however higher for V_{DS} = 5V as compared to V_{DS} = 10V (Fig. 11a) as higher electric field increases de-trapping and leads to lower V_{TH} shift with UV exposure. Finally, non-destructive nature of the UV assisted probing is depicted in Fig. 12, which shows complete recovery even with longer exposure time and multiple exposures. UV exposure only activates the traps already present at the GaN/insulator interface and does not introduce traps in the system.

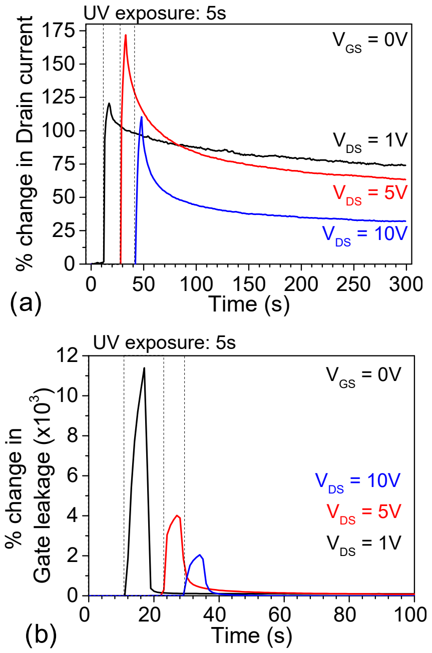

Figure 11. % change in (a) I_D and (b) I_G with time for different drain voltage (V_{DS}), depicting faster recovery of I_D and I_G post UV exposure when V_{DS} was increased. Enhanced field leads to increased carrier injection and subsequent detrapping of traps (V_{GS} = 0V to negate V_{GS} induced recovery).

IV. Conclusion

This work reports a fast and non-destructive probing of deep level traps in gate dielectric/GaN interface of GaN MISHEMTs by using UV light. The study reveals deep level donor traps that can lead to I_G and V_{TH} instabilities in GaN MISHEMTS, thereby providing essential insights for improving oxide/GaN quality. The V_{TH} and I_G can be recovered by injecting electrons during gate sweep. The gate bias is a control knob to trigger the de-ionization process at different energy levels whose trap relaxation time can be evaluated from the corresponding recovery transient.

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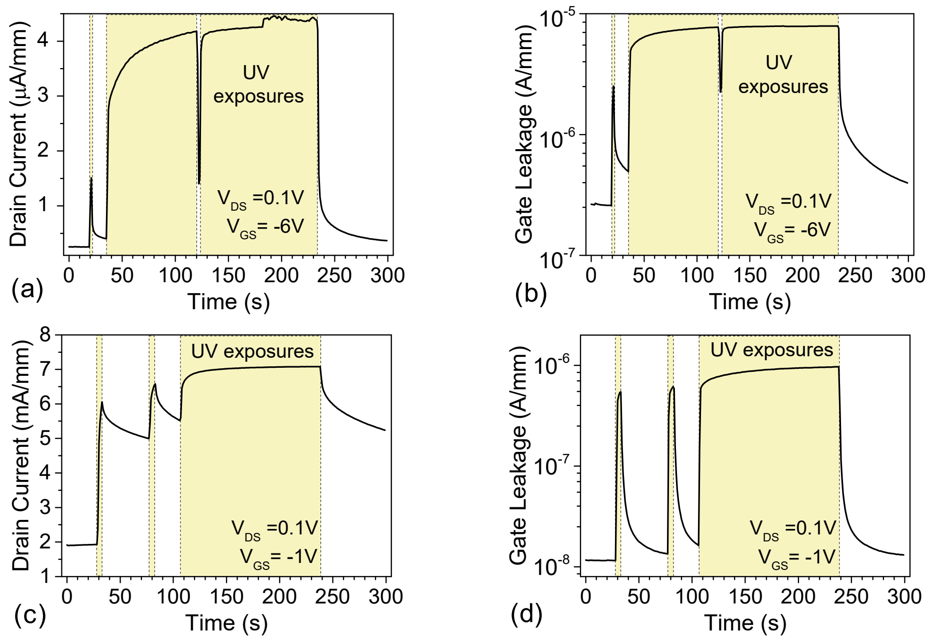

Figure 12. Impact of multiple UV exposures and long exposure times on I_D and I_G and its recovery in (a)-(b) OFF state and (c)-(d) ON-state. I_D and I_G are non accumulative under multiple UV exposures and saturates during long exposures indicating that the UV exposure only activates the deep traps already present in the system and does not lead to trap generation.

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