

# 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- $\kappa$  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.

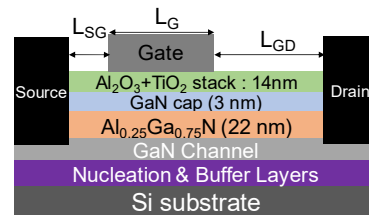


Figure 1. Cross-sectional view of AlGaN/ GaN HEMTs studied in this work.

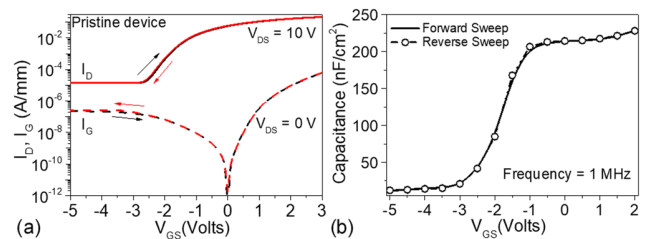


Figure 2. (a) Transfer characteristics, Gate leakage and (b) dual sweep C-V of pristine HEMT showing superior performance with negligible hysteresis, indicating excellent gate oxide/GaN interface quality.

## 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

2DEG density at the AlGaIn/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  $I_G$ .

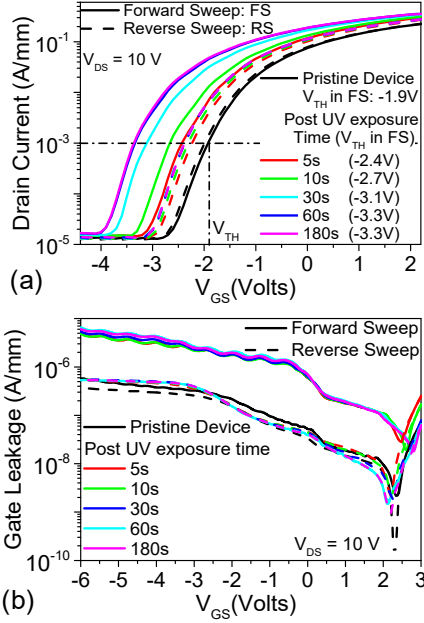


Figure 3. Dual sweep (a)  $I_D$ - $V_{GS}$  characteristics depicting negative shift in  $V_{TH}$  with increasing UV exposure time and (b)  $I_G$ - $V_{GS}$  characteristics depicting increased  $I_G$  in forward sweep, due to excitation of (positively charged) deep donor traps.

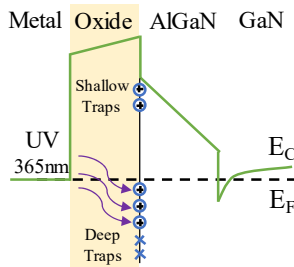


Figure 4. Schematic depicting excitation of deep-level traps at gate oxide/GaN interface by using UV.

### 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  $\sim 30$ s 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  $\sim 2x$  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  $\sim 30$ s 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  $>120$ s to be associated with  $V_{TH}$  shift, or (ii) absence of carriers at the AlGaIn 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.

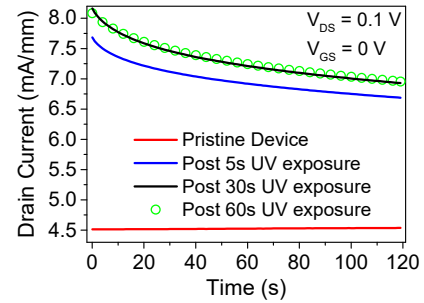


Figure 5. Dual sweep (a)  $I_D$ - $V_{GS}$  characteristics depicting negative shift in  $V_{TH}$  with increasing UV exposure time and (b)  $I_G$ - $V_{GS}$  characteristics depicting increased  $I_G$  in forward sweep, due to excitation of (positively charged) deep donor traps.

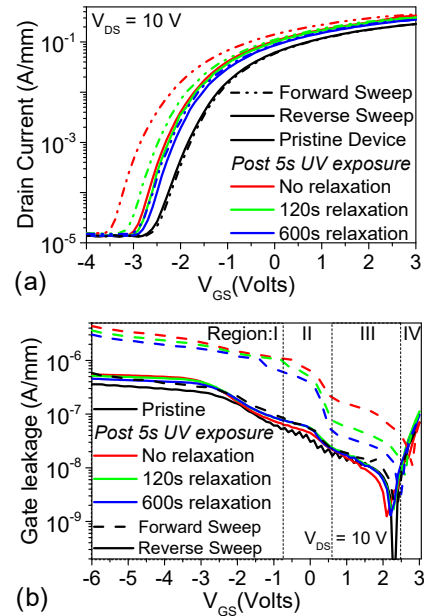


Figure 6. Post 5s UV exposure, (a) dual sweep  $I_D$ - $V_{GS}$  characteristics, shows reduction in hysteresis and slow  $V_{TH}$  recovery, measured after increasing relaxation times. (b)  $I_G$ - $V_{GS}$  characteristics, measured after increasing relaxation times, exhibits four distinct regions. 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  $I_G$

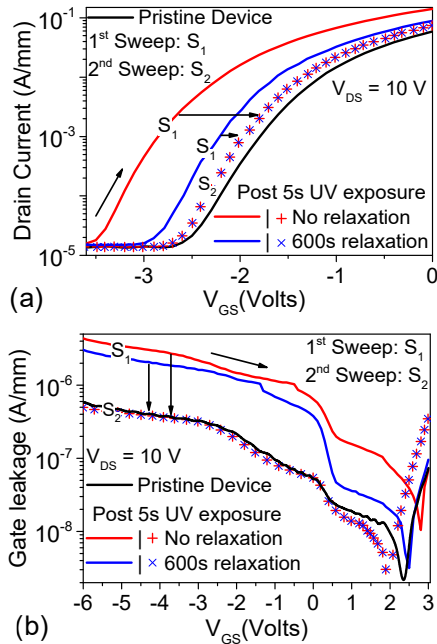


Figure 7. (a)  $I_D$ - $V_{GS}$  and (b)  $I_G$ - $V_{GS}$  characteristics of pristine device compared with the same post 5s UV exposure. It shows complete  $V_{TH}$  and  $I_G$  recovery by a second  $I_D$ - $V_{GS}$  sweep immediately following the first sweep, irrespective of the relaxation time,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

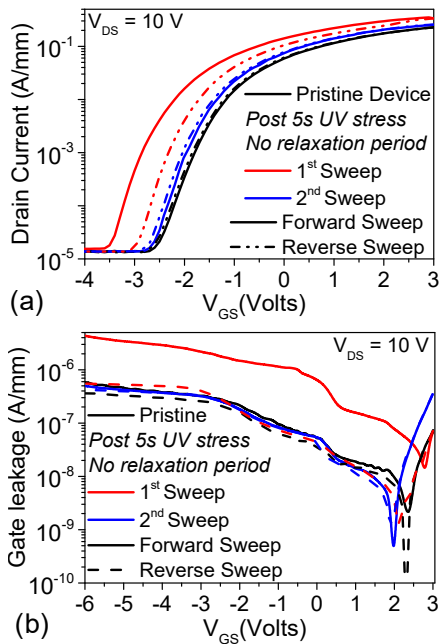


Figure 8. Post 5s UV exposure, two consecutive (a)  $I_D$ - $V_{GS}$  and (b)  $I_G$ - $V_{GS}$  sweeps carried out without any relaxation period.  $V_{TH}$  and  $I_G$  recovers to pristine level following the two sweeps even without any relaxation post UV exposure.

(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.

#### 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,

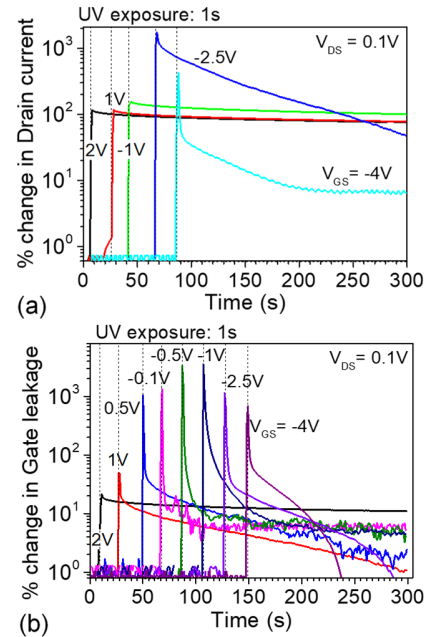


Figure 9. (a)  $I_D$  and (b)  $I_G$  measured with time for different  $V_{GS}$  post 1s of UV exposure. Sweeping  $V_{GS}$  towards negative initiates the recovery process due to trap deionization by electron injection. Faster recovery time with negative  $V_{GS}$  shift indicates detection of shallower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

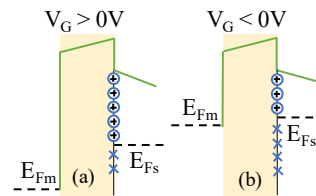


Figure 10. Schematic band diagram of metal/oxide/AlGaN stack under (a) positive  $V_{GS}$  and (b) negative  $V_{GS}$  showing gate bias as a control parameter to scan the trap energy levels. Negative  $V_{GS}$  shifts Fermi energy upwards, providing electrons to deionize positively charged donor traps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

#### 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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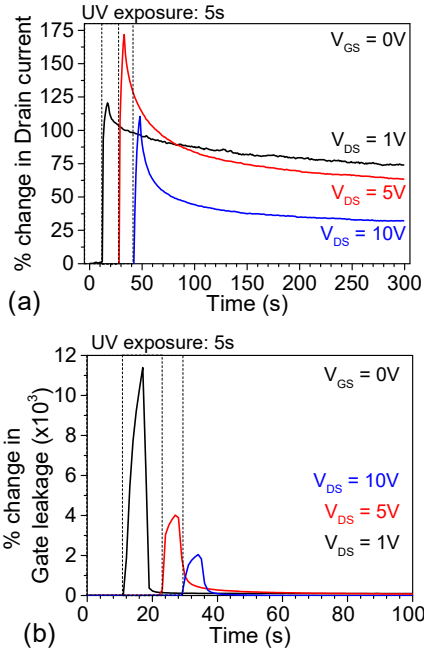


Figure 11. % change in (a)  $I_D$  and (b)  $I_G$  with time for different drain voltage ( $V_{DS}$ ), depicting faster recovery of  $I_D$  and  $I_G$  post UV exposure when  $V_{DS}$  was increased. Enhanced field leads to increased carrier injection and subsequent de-trapping of traps ( $V_{GS} = 0V$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

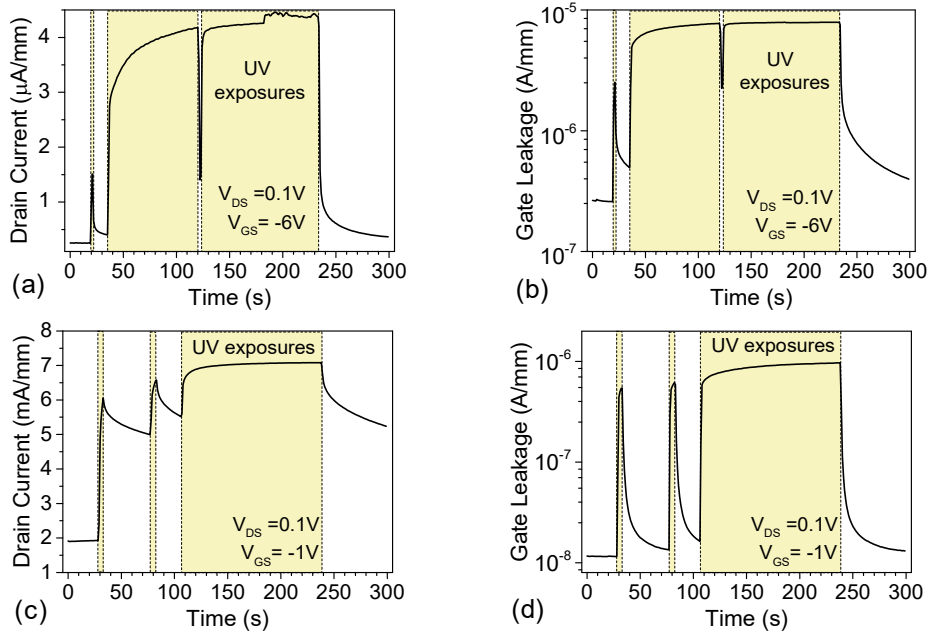


Figure 12. Impact of multiple UV exposures and long exposure times on  $I_D$  and  $I_G$  and its recovery in (a)-(b) OFF state and (c)-(d) ON-state.  $I_D$  and  $I_G$  are non accumulative under multiple UV exposures and saturates during long exposures indicating that the UV exposure only activates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

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