E_C-0.90 eV Trap-Induced Threshold Voltage Instability in GaN/Si MISHEMTs

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Abstract

In this study, AlGaN/GaN MISHEMTs exhibited a −2 V threshold voltage (V_T) instability after biasing with large off-state drain voltage. Isothermal box-car analysis was applied on the MISHEMTs threshold voltage transients to reveal an E_C-0.90 eV trap located in the GaN buffer layer. At the end, a model is developed for the trap's impact on the two-dimensional electron gas (2DEG) revealing how the trap acts as a back gate, causes a large negative V_T instability, and how this is possible without leading to significant buffer leakage current.

INTRODUCTION

AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MISHEMTs) are commercially available but often derated significantly to avoid the impact of traps at higher voltages. GaN's high Baliga's figure of merit allows higher voltages with lower on-resistance (R_{ON}), but traps can cause significant threshold voltage stabilities issues. There are a few papers that talk about trap-induced V_T instabilities of GaN/Si MISHEMTs due to electrical stressing [1-4]. However, very few of those works have assigned the V_T effect to specific traps. Here, we identified a trap at E_C-0.90 eV in an industry AlGaN/GaN MISHEMT on (111) Si (Fig.1a) that directly causes a large threshold voltage (V_T) instability. We show this trap is located in the GaN buffer through several experiments including comparison with capacitance-based DLTS results on AlGaN/GaN Schottky diodes (Fig. 1b) and bulk GaN sample. Finally, the spatial distribution and possible physical source of this trap level are discussed.

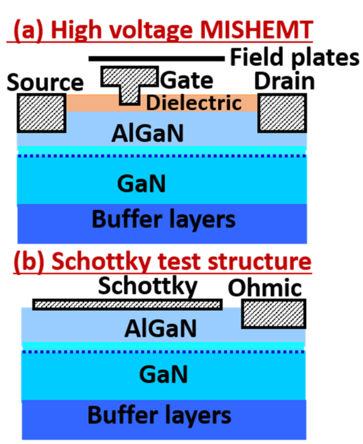

Fig. 1. (a) Sample structure of the AlGaN/GaN MISHEMT; (b) Schottky diode test structure used for bulk defect measurements and to eliminate any influence of the dielectric layer.

RESULTS AND DISCUSSION

After high-voltage (HV) off-state stressing ($V_{DS} \geq 40$ V), these industry-provided MISHEMTs exhibited a –2.0 V threshold voltage shift measured from comparison of 50 μs double-pulsed transfer I-V curves using a zero quiescent condition ($V_{GS} = 0$ and $V_{DS} = 0.0$ V) and high V_{DS} quiescent condition ($V_{GS} < V_T$ and $V_{DS} = 40.0$ V), as shown in Fig. 2. The negative V_T instability indicates an electron de-trapping process under the gate during high off-state V_{DS} with a temperature-dependent time constant. The V_T shift was completely recoverable but the process was slow where V_T recovery 75% after 12 h. To identify the trap responsible, the V_T transient was recorded by biasing the device at 400 V on V_{DS} with the gate pinched off for 100 ms to begin emitting trapped electrons then recording the gate voltage required to maintain 5 μA/mm with 10 V on the drain for 50 μs. Thus,

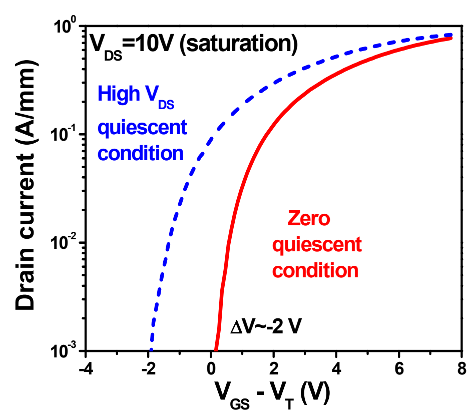

Fig. 2. Double-pulsed transfer I-V curve comparison between zero quiescent condition (V_{GS}=0 and V_{DS}=0 V) and high V_{DS} quiescent condition ($V_{GS}<V_T$ and V_{DS}=40 V). The voltage axis was normalized by setting the nominally zero current of the red curve to 0 V.

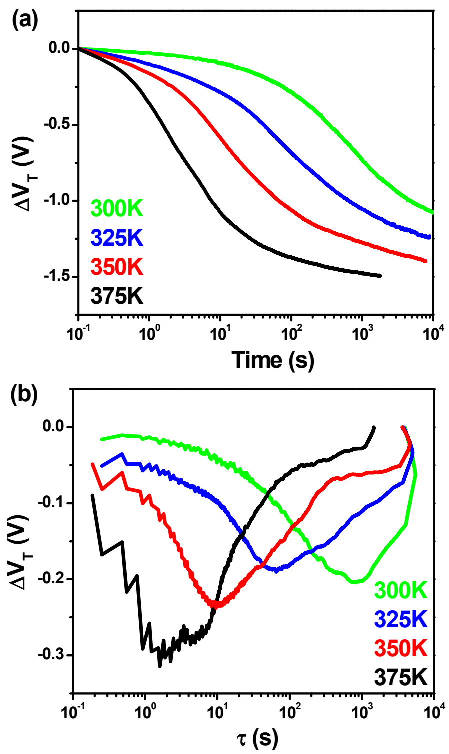

Fig. 3. (a) V_T transients (normalized) were recorded at different baseplate temperatures after biasing the device at 400 V V_{DS} (off-state) for 100 ms then recording the gate voltage required to maintain 5 μA/mm at 10 V drain voltage for 100 μs and repeat this for 3 h. It shows temperature dependent negative V_T shift ~ -1.5 V, indicates the E_C-0.90 eV trap accounts for a majority of the V_T instability; (b) Isothermal boxcar analysis applied on the obtained V_T transients from (a) where the negative peak positions give the transient time constant for each temperature.

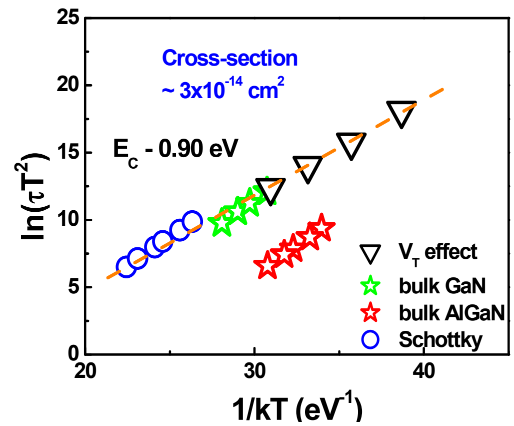

Fig. 4. Arrhenius plot of the trap data from Fig. 3b (triangles), the Schottky diode on the same material (circles), and previous studies of bulk GaN [10] and AlGaN[11]. The E_C-0.90 eV trap in the MISHEMTs matches the bulk GaN defect indicating the MISHEMT trap is likely a GaN buffer trap.

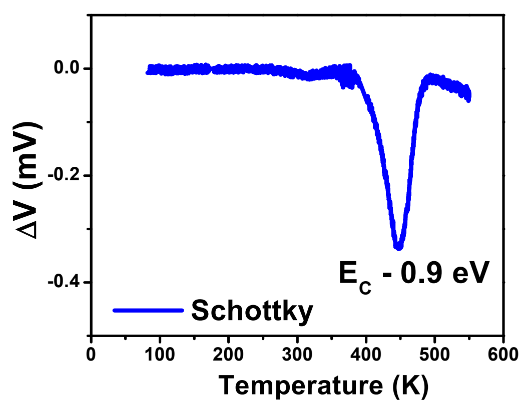

Fig. 5. DLTS measurement on AlGaN/GaN Schottky diodes, which is mostly sensitive to traps in GaN layer due to its large depletion in GaN. This DLTS reveals same E_C-0.90 eV trap as the measurements on MISHEMTs, as shown in Fig. 4.

99.5% of the time is at the stressing condition where trapping occurs, and 0.5% of the time is devoted to measuring V_T. This process was repeated for 3 hours to record the V_T time dependence. The V_T instabilities were measured at 300, 325, 350, and 375 K and the time constants of the transients were extracted using isothermal boxcar analysis, which is shown in Fig. 3 [5]. The Arrhenius plot in Fig. 4 of the trap time constants revealed a trap with energy E_C-0.90eV and ~3×10^{-14} cm^2capture cross section. The trap concentration (sheet)for the threshold voltage shift in Fig. 2 can be estimated using [6, 7, 8]:

$$n_T = -\frac{\varepsilon_{\mathrm{AlGaN}}}{\mathrm{qd}}\Delta \mathrm{V_T}$$

where n_T is the trap concentration (sheet), ε_{AlGaN} is the permittivity of the AlGaN barrier, and d is the AlGaN layer thickness. The obtained trap concentration is ~ 2.5×10^{12} cm^{-2}.

To investigate the source and physical location of the E_C-0.90 eV trap, AlGaN/GaN Schottky diodes (Fig. 1b) were fabricated on the same wafer, but without a dielectric layer on the AlGaN. Deep level transient spectroscopy (DLTS) measurements were performed on the Schottky diodes with a large depletion in GaN during the measurement to be mostly sensitive to traps in the GaN layer (Fig. 5) [9], which revealed the same E_C-0.90eV trap as the MISHEMT isothermal results in Fig. 3. This indicates the trap is definitely not in the dielectric layer since this layer is not present in the Schottky diode sample, but instead it is likely to be a GaN buffer trap since traps in the GaN region dominated the signal. Additionally, the E_C-0.90 eV trap is also consistent with the GaN trap reported previously (also shown in Fig. 4) [10], but inconsistent with traps with similar energies in AlGaN [11]. In addition, the magnitude of the V_T instability shows strong V_{GD} dependence where TCAD modeling reveals that the V_T instability is only observed when significant positive band bending is present in the GaN buffer to allow for emission of trapped electrons. All above results indicate the E_C-0.90 eV trap is very likely in the GaN buffer.

As for the physical source of this deep level, this has been previously studied. A series of DLTS measurements with different filling pulsed time (t_P) were performed on MBE-grown n-GaN sample [10]. The DLTS signals showed a clear linear relationship with log (t_P), suggests an extended defect with linear arrangement [12] which is consistent with point defects segregated to dislocations [13]. In addition, this E_C-0.90 eV trap was also observed in MOCVD-grown n-GaN after He-ion irradiation [14] and HVPE-grown n-GaN sample [15], and its concentration is sensitive to proton irradiation, which indicates it is likely to be related to intrinsic defects in n-GaN.

This work demonstrates how a GaN defect with energy E_C-0.90 eV can cause large negative V_T shifts (-2 V) through a process of back gating the device with slow recapturing/recovery rates. This trap was previously revealed to exhibit extended trapping behavior and potentially located near threading dislocations, but additional work is needed to confirm the physical source of this level that can have significant impact on GaN-based transistors.

Acknowledgements

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Acryonyms

MISHEMT: Metal-Insulator-Semiconductor High Electron Mobility Transistors
2DEG: Two-Dimensional Electron Gas
R_{ON}: On-Resistance
V_T: Threshold Voltage
HV: High Voltage
DLTS: Deep Level Transient Spectroscopy
TCAD: Technology Computer-Aided Design