An abstract submitted to *the 2014 CS MANTECH: May 2014,* Denver, USA

Observation on Slow Carrier Trapping in AlGaN/GaN Schottky and MIS Diodes

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III-nitride (III-N) heterojunction field-effect transistors (HFETs) and metal-insulator-semiconductor field-effect transistors (MISFETs) are among a few of promising switching devices for next-generation high-power applications. Nevertheless, the carrier trapping phenomenon that often leads to a threshold voltage shifting during the switching cycles could be problematic for the realization of robust operation using III-N FET-based switches. In this work, we present a simple and effective C-V method to evaluate the off-state threshold voltage instability in III-N FETs and observed a slow-trap-induced threshold voltage shifting phenomenon in the C-V characteristics of AlGaN/GaN Schottky barrier diodes (SBDs) and metal-insulator-semiconductor (MIS) diodes. Using variable durations of the off-state voltage stressing, V_{th} for SBDs shifts toward more positive values as the off-state stressing time increases. On the contrary, the V_{th} of MIS diodes shifts toward a more negative value in the same stressing test. The long time constants of these states also suggest that the carrier trapping may be attributed to deep-level traps in AlGaN layer for SBDs. Additional positive oxide charges in the gate insulator also participate in threshold voltage shifting during the off-state stressing. The value of threshold voltage shifting also can provide an estimation on the density of trapped carrier by using an equivalent model of capacitors This phenomenon can be understood using a slow-state carrier-trapping mechanisms and can be directly applicable to the performance evaluation of III-N HFETs and MISFETs.

In this study, two samples from the same wafer were processed in the same batch processing except for an additional ALD-grown Al_2O_3 gate insulator was deposited on one of the samples. After the ohmic contact and a Ni-based gate metallization, C-V measurements were performed on a circular-shaped diodes with 50 μm radius. These devices were first stressed at V_G = -5 V (-2.5 V below V_{th}) for a designated time before each C-V sweep was measured. The stressing time was then sequentially increased with up to 20 minutes. A measured C-V characteristics of an AlGaN/GaN SBD is shown In Figure 1. By plotting V_{th} against the off-state stressing time (Figure 2), we observed that V_{th} shifted toward positive after each off-state stress and V_{th} shifting reached a nearly constant value of 0.4 V after 1200 s of off-state stressing. The threshold shift seems to follow an exponential relationship with a time constant of 340 s. The time constant represents the time require to fully trap electrons in the off-state stressing prior to the measurement. The trap state density (Q_{trap}) can also be estimated as 7E11 cm^{-2} ($Q_{trap} = C_{AlGaN} \cdot \Delta V_{th,\, AlGaN}$). Unlike the shallow traps that has a relatively short trapping/de-trapping life time (~30 ms in HFETs [1]), the trapping processes observed in the off-state stressing experiment shows a slow process and can be attributed to the deep-level traps, such as carbon-induced traps or gallium vacancies in the AlGaN layer [2].

The same measurement procedures were exercised on AlGaN/GaN MIS diodes with a 10-nm thick ALD Al_2O_3 as the insulator. As shown in Figure 3, a negative threshold voltage shifting was measured, which shows an opposite trend as seen in the case of SBDs. The fitted time constant is 308 s on the MIS diode. The negative shifting may be attributed to the electron depletion in the gate insulator. When the electrons were depleted by negative V_{GS}, the positive oxide charge in the ALD Al_2O_3 layer that compensates the positive potential shift arising from the negatively charged trap centers in the AlGaN layer, leading to a negative shift of the threshold voltage as the stressing time increases. Assuming the density of trap in AlGaN layer is the same to that in SBDs, the density of fixed oxide charge can be estimated as 5.5E12 cm^{-2} using a series capacitance model.

In summary, we studied C-V characteristics of SBDs and MIS diodes using an off-state stress method. Slow trap states were observed in the AlGaN barrier layer. In addition, the positive oxide charge in the ALD-grown Al_2O_3 are also identified as a slow state that induced a negative V_{th} shift with increased off-state stressing time. The proposed off-state stressing method reveals the slow-state nature of the traps and provides a simple and effective way to quantify the trap states and oxide charges in III-N MISFETs

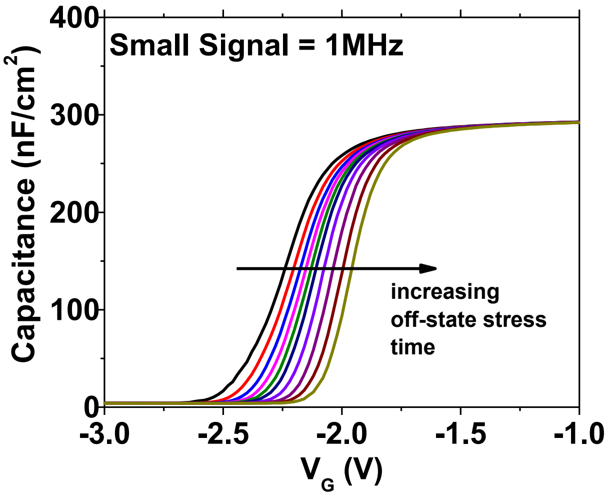

Figure 1 The measured C-V characteristics of the AlGaN/GaN Schottky diode after different stress time.

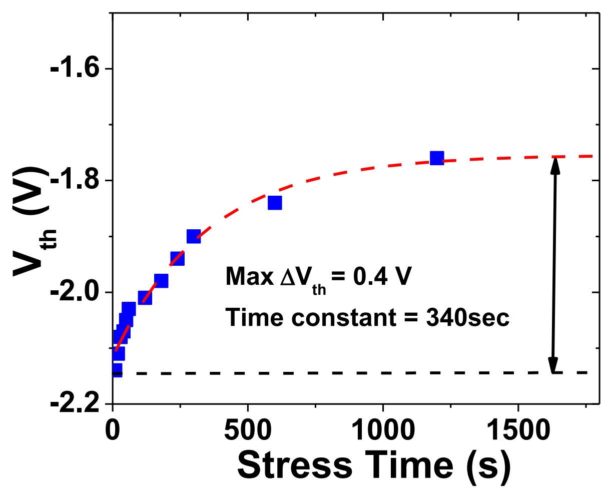

Figure 2 The relationship between the threshold voltage shift and the stress time on the AlGaN/GaN Schottky diode.

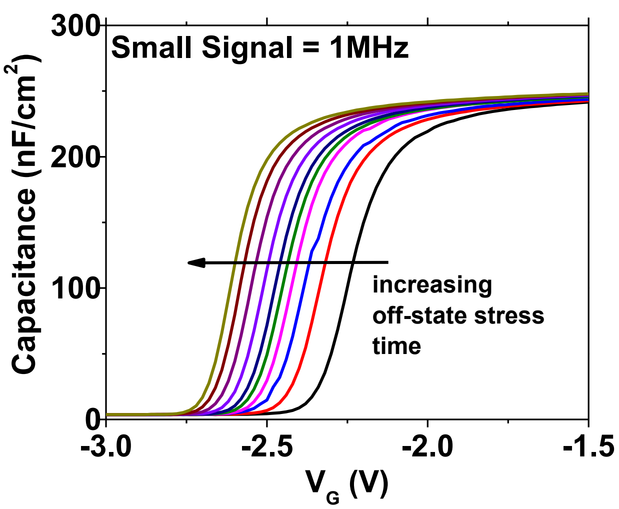

Figure 3 The measured C-V characteristics of an Al_2O_3/AlGaN/GaN MIS diode after different stress time.

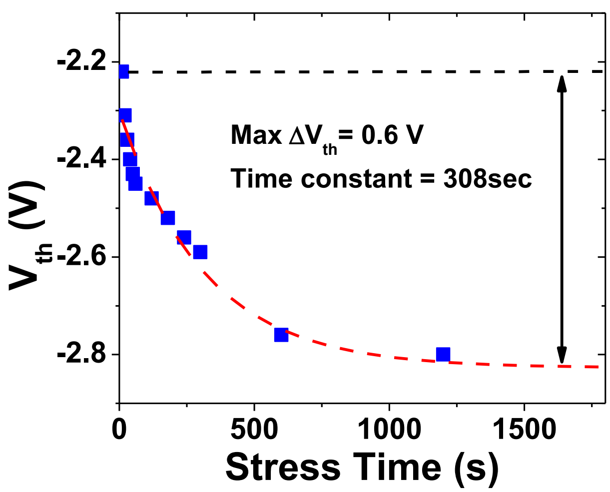

Figure 4 The relationship between the threshold voltage shift and the stress time on the Al_2O_3/AlGaN/GaN MIS diode.

Reference:

[1] A. Sasikumar, *et al.*, "Direct comparison of traps in InAlN/GaN and AlGaN/GaN high electron mobility transistors using constant drain current deep level transient spectroscopy," *Applied Physics Letters*, vol. 103, pp. 033509, 2013
[2] A. R. Arehart, *et al.*, "Next generation defect characterization in nitride HEMTs," *Phys. Status Solidi C*, vol. 8, no. 7–8, pp.2242–2244, 2011