E$_C$-2.0eV trap-related dynamic R$_{ON}$ in GaN/Si MISHEMTs

W.Sun[1], A. Sasikumar[1], J. Joh[2], S. Krishnan[2], A. Arehart[1a] and S. Ringel[1]

[1]Department of Electrical and Computer Engineering, the Ohio State University
Columbus, Ohio 43210, USA.

[2]Texas Instruments, Dallas, TX 75243 USA

[a]Corresponding author: Aaron Arehart, arehart.5@osu.edu, 614-205-2012

AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MISHEMTs) for high voltage switching applications are promising due to the ability to simultaneously achieve high breakdown voltage and low on-resistance beyond the theoretical limits of Si technology [1]. However, electrically active defects in these structures can negatively impact the device operation leading to increasing static on-resistance (R$_{ON}$), dynamic R$_{ON}$, and threshold voltage instabilities [2]. In this work, we correlated degradations to a specific trap, identified its physical location and possible physical source through advanced MISHEMT-based high voltage defect spectroscopy.

The AlGaN/GaN MISHEMTs in this study were fabricated on a Si (111) substrate with a dielectric layer in the access regions and under the gate. Multiple field plates were optimized to achieve a breakdown voltage in excess of 600V. On the same wafer, 300 μm x 300 μm AlGaN/GaN Schottky diodes were fabricated without the dielectric layer to investigate the location and physical source of the trap(s).

At large off-state V$_{DS}$, the MISHEMTs exhibited large dynamic R$_{ON}$ with a ~400 s time constant (Fig. 1a). An onset to the dynamic R$_{ON}$ is evident in Fig. 1b with a threshold at 200 V, and the dynamic R$_{ON}$ reaches ~15X higher than the static R$_{ON}$. If the dynamic R$_{ON}$ recovers due to thermal emission from a defect state, the dynamic R$_{ON}$ would exhibit strong temperature dependence, but Fig. 2 shows the dynamic R$_{ON}$ transients are temperature independent. To further explore the trap(s) responsible for the dynamic R$_{ON}$, constant drain current deep level optical spectroscopy (CI$_D$-DLOS) measurements were used [3]. The sample was subjected to off-state V$_{DS}$ biasing of 250 V then the dynamic R$_{ON}$ transient was recorded with the sample subjected to monochromatic light. In Fig. 3 the steady-state R$_{ON}$ is plotted after 100 s with monochromatic light shining. This time is significantly shorter than the dynamic R$_{ON}$ time constant so if the photon energy is lower than the trap energy. If the trap emission is stimulated optically (i.e. hv>E$_C$-E$_T$), the dynamic R$_{ON}$ will quickly return to the static R$_{ON}$. Fig. 3 shows a single onset in the dynamic R$_{ON}$ where it recovers with optical energies above 2.0 eV indicating a single trap at E$_C$-2.0 eV that is also responsible for the temperature-independent recovery (~300 s in Fig. 2). From the recovery and using the model to estimate trap concentrations in HEMTs [4], the trap density of this level was estimated to be 9.6×10^{12} cm^{-2}, which is very close to the 2DEG concentration and explains the large R$_{ON}$ change. To identify where the defect is located in the MISHEMT structure and possible physical source, the Schottky diodes were used.

To determine the defect location, AlGaN/GaN Schottky diodes were used. Fig. 4 shows the capacitance-based deep level optical spectroscopy measurements with a depletion depth of 0.7 μm, which was almost entirely in the GaN buffer layer. Figure 4 shows the same E$_C$-2.0 eV trap as the MISHEMT measurements. The fact that the depletion is almost entirely in the GaN buffer means the measurement is mostly sensitive to traps in the buffer, so the presence of the E$_C$-2.0 eV trap in the DLOS suggests the E$_C$-2.0 eV is a GaN buffer trap.

To confirm the location of the E$_C$-2.0 eV trap, nanometer-scale deep level optical spectroscopy (nano-DLOS) was performed on the AlGaN/GaN Schottky device. Nano-DLOS is a scanning probe microscopy technique where the surface potential is monitored at a fixed position. This allows lateral mapping of defect concentrations and the presence of the 2DEG at the AlGaN/GaN interface acts to screen any trap response in the GaN from the nano-DLOS tip. The nano-DLOS results in Fig. 5 show little evidence of an E$_C$-2.0 eV level nor evidence of other typical GaN peaks such as E$_C$-3.28 eV. The only feature in the AlGaN layer is the E$_C$-3.76 eV trap previously observed in similar AlGaN material [5]. Additional evidence to the location and source of this level is available from previous studies of carbon incorporation in n-type GaN. It was found that carbon contributed to several deep levels in n-type GaN co-doped with Si and C, but C led to a level forming at E$_C$-1.94 eV, which is very similar to the E$_C$-2.0 eV level reported here indicating these levels may be the same trap [6]. These traps are negatively charged when they capture an electron, which leads to a 2DEG reduction and increased R$_{ON}$ (dynamic R$_{ON}$).

It is demonstrated that a large dynamic R$_{ON}$ is present in the MISHEMTs studied and this is due to a high concentration of E$_C$-2.0 eV traps in the GaN buffer that are possibly related to the presence of carbon. This suggests that careful buffer design and limiting carbon incorporation is necessary to improve MISHEMT performance.

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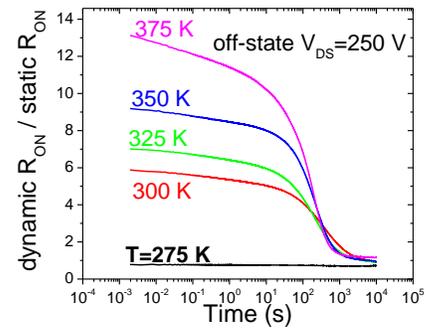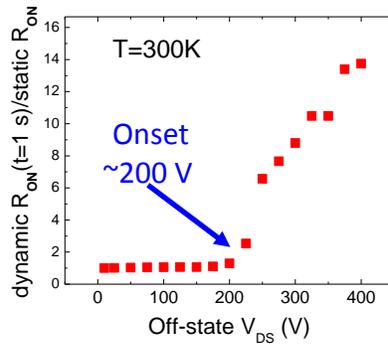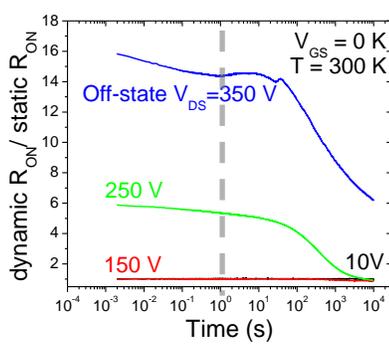[4] A. Arehart et al., *Proc. 2010 IEEE International Electron Devices Meeting (IEDM),* 20.1.1 (2010).

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Fig.1. (a) On-resistance transients recorded in the triode regime after biasing to different off-state V_{DS} conditions plotted relative to the static R_{ON}. Up to 150 V off-state V_{DS}, no significant increase in dynamic on-resistance was observed. (b) On-resistance sampled at 1 s after switching the MISHEMT. A sharp onset at 200 V and capacitance voltage measurement of the MISHEMTs indicate that significant dynamic R_{ON} take place only after an electric field threshold is exceeded at the edge of the longest field plate where the electron trapping likely

Fig.2. On-resistance transients recorded in triode conditions after biasing to off-state V_{DS} =250 V for different baseplate temperatures. The time constant of the dynamic R_{ON} transient has negligible temperature dependence, which suggests a non-thermally activated trap.
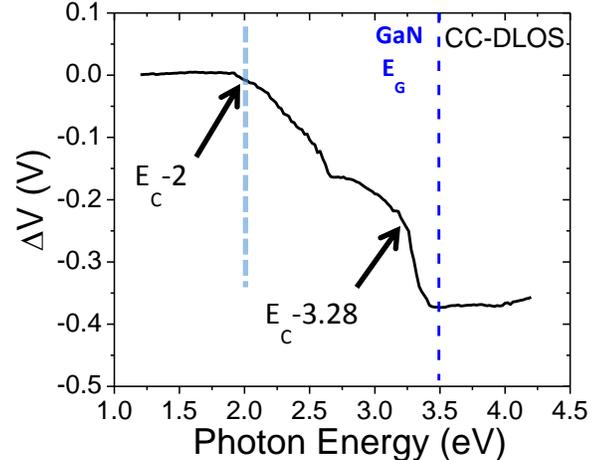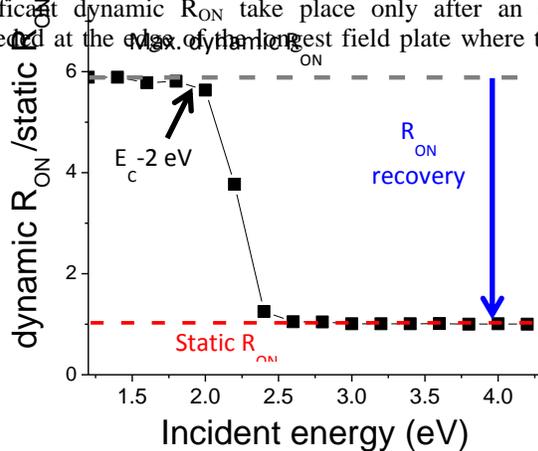

Fig.3. Constant drain current DLOS results from the MISHEMT. In the dark and at incident photon energies < 2.0 eV, R_{ON} remained approx. constant at the peak dynamic R_{ON} (~6X higher than the static R_{ON}) for >>100 s after switching from off-state V_{DS} = 250 V. With light energies > 2.0 eV, R_{ON} recovers to the static R_{ON} in <20 s. The sharp negative onset at 2 eV indicates an E_C–2.0eV electron trap is directly linked to the dynamic R_{ON}.

Fig.4. Constant capacitance DLOS on the AlGaN/GaN Schottky test structure biased deep into depletion to be mostly sensitive to GaN buffer traps shows the E_C-2.0 eV trap. The absence of AlGaN traps and the common E_C-3.28 GaN trap indicates the measurement is indeed mostly GaN sensitive. This result indicates the E_C-2.0 eV trap is likely in the GaN buffer.
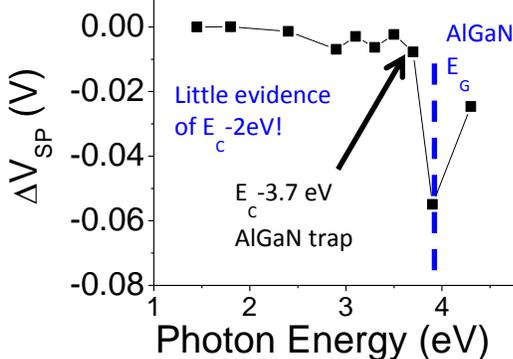

Fig.5. Nano-DLOS measurements sensitive to traps only in the AlGaN reveal no sign of the E_C–2.0 eV trap where the trap was expected to have an amplitude of ~0.16 V if it was present in the AlGaN layer. This result confirms the E_C-2.0 eV trap is a GaN buffer trap.
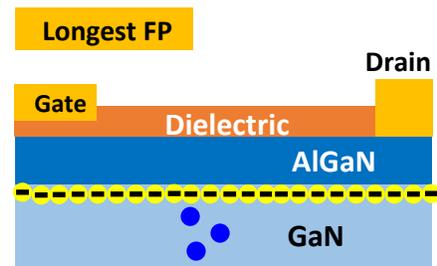
Fig.6. Schematic cross section of the GaN/Si MISHEMT shows the likely location of the E_C-2.0eV traps that are modulated with applied bias in the device (in the GaN buffer and at the edge of the last field plate where the electric fields are maximum. A level forms in GaN at E_C-1.94 eV due to C incorporation and this is possibly the physical source of this level in the GaN buffer. [4]