Abstract—The pinch-off voltage ($V_{TH}$) of AlGaN/GaN high electron mobility transistors (HEMTs) was measured that was showing the shift from -5.2 V at 300 K to -4.2 V at 450 K in transfer characteristics on low drain voltages. This anomalous shift in $V_{TH}$ can be inferred as the electron trapping in access region near the gate and/or bulk under the gate at elevated temperatures. The comparable shift in $V_{TH}$ was also observed with UV exposure of the device. The possible locations and charge concentrations of traps responsible for this anomalous drift in $V_{TH}$ have been simulated in Silvaco ATLAS. The same amount of change in $V_{TH}$ can be produced from the trapped charges in access region near the gate or in bulk including AlGaN/GaN interface; however, trapped charge concentration of the order of -1e13 cm$^{-2}$ is required near the gate metal in comparison to -1e12 cm$^{-2}$ near the channel. Furthermore, the reduction in the drain current at zero gate voltage on higher temperatures can be attributed to the reduction in the low field mobility due to phonon scattering and trapping in the access region.

Index Terms—AlGaN/GaN HEMT, threshold / pinch-off voltage, trapping.

I. INTRODUCTION

AlGaN / GaN high electron mobility transistors (HEMTs) have emerged as the preferred device in high power at RF frequencies owing to its high power output and power added efficiency in contrast to the GaAs and Si technology. GaN on Si is being promoted by the commercial markets whereas GaN on SiC remains the preferred choice in the defense applications due to smaller lattice mismatch and high thermal conductivity despite being costly. This technology has achieved state of the art power densities of 40 Watt/mm in C-band [1], however, it still suffers from several reliability issues such as current collapse [2-4], gate leakage [5], and early degradation [6]. Generally, the threshold voltage ($V_{TH}$) or pinch-off voltage of AlGaN/GaN HEMTs does not change with the increase of the device temperature [6]. However, anomalous shift in $V_{TH}$ was observed in these devices.

In this paper, we have studied the possible reasons of $V_{TH}$ shift due to the trapping / detrapping of electrons. In order to study the trapping, the transfer characteristics at low drain voltages were obtained at different temperatures. The visible $V_{TH}$ shift in these characteristics was simulated in Silvaco ATLAS by putting the trapped charges near and under the gate at different distances from the metal-semiconductor interface. The concentrations of trapped charges have also been varied to simulate the $V_{TH}$ shift in the device structure. Section II presents the detail of the experiment and Section III details the discussion and results of AlGaN/GaN HEMTs.

II. EXPERIMENTAL DETAILS

AlGaN/GaN HEMTs used in the study are in-house fabricated using MOCVD grown hetero-structures on SiC substrate. The sheet resistance of epitaxial layers is 264 Ohms/□ consisting of 2.1 µm thick buffer, 1 nm AlN spacer, 25 nm AlGaN barrier having 28% Al concentration, and 1.5 nm GaN cap layer. These devices have Ti/Al/Ni/Au ohmic and Ni/Au Schottky contacts and 100 nm thick Si$_3$N$_4$ passivation layer using Plasma Enhanced Chemical Vapor Deposition technique.

The drain current ($I_D$) is measured at low drain voltages ($V_D$) of 0.2 V by varying the gate voltage ($V_G$) from -6 V to
0 V using Keithley 2651A and 2611B source meters respectively. The temperature of this device is varied from 300 K to 450 K in Accent cryostat. The transfer characteristics are also measured in the presence of UV light of a commercial LED source in addition to the bias stress of $V_G = -10$ V and $V_D = 10$ V for nearly 300 seconds. The schematic of the AlGaN/GaN HEMT is shown in Fig. 1.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the measured $I_D-V_G$ curves at different temperatures that have been compared with the simulated curves in Silvaco ATLAS. This structure was simulated with 28% Al concentration, 28 nm thick AlGaN barrier, 2 µm thick buffer, and 1.2e13 cm$^{-2}$ two dimensional electron gas (2-DEG) concentration in the channel. Electric Field dependent mobility model is used with the low field mobility of 1100 cm$^2$/V-s and 2e16 cm$^{-3}$ bulk trap density at 1.0 eV from the conduction band. The simulated results are matched with measured data at 300 K. The reduction in $I_D$ at zero gate voltage is also observed in the simulation similar to the observation in measured currents; however, the shift in $V_{TH}$ could not be simulated by varying the temperature of the simulation. It indicates that there is an additional trapping mechanism present inside the device which is responsible for this $V_{TH}$ shift. The possible locations of these additional traps are (a) bulk region under the gate from 2 nm below the metal-semiconductor interface to 70 nm in the GaN buffer, (b) access region at AlGaN/$\text{Si}_3\text{N}_4$ interface near the metallurgical gate.

The effect of bulk trap charges on $V_{TH}$ with concentrations ranging from 1e10 cm$^{-2}$ to 3e13 cm$^{-2}$ has been plotted in Fig. 3 by assuming the presence of charges at different locations under the gate. It can be seen from this figure that $V_{TH}$ can be shifted from -5.2 V to -4.2 V by putting the charges anywhere in the simulated location’s range; however, increased concentration of trapped electrons is required to shift $V_{TH}$ by same amount if these are located away from the AlGaN/GaN interface. To obtain this shift, the required trap concentrations near the AlGaN/GaN interface are 1.5e12 cm$^{-2}$ that would correspond to the 1.5e19 cm$^{-3}$ trap density. If this amount of traps density is present in the bulk then this $V_{TH}$ shift can be attributed to these traps. However, this point needs to be investigated further.

Fig. 4 depicts the typical simulated view graphs of traps present 2 nm below the gate and compared with the measured results at 450 K. Similar results can be simulated for other locations by varying the trapping concentrations. It can be seen from this figure that change in the $V_{TH}$ requires 2.5e13 cm$^{-2}$ trap concentrations. These traps concentrations are available at top AlGaN surface in the form of surface states which are the origin of electrons in 2-DEG channel [7]. However, gate-metal may not allow the surface states present just under the gate to change its potential independently from the metal work function and electron affinity of the semiconductor [8]. Therefore, the possibility of trapping in the access region near the gate edge has been also explored. As we can see from this figure that trap charges in the access region can also produce the shift in $V_{TH}$. In this case, this shift is similar to the fixed oxide
charges. The depletion region of Schottky contact is also extended in the access region of the HEMTs [9], therefore, the bias dependence of \( V_{TH} \) shift should also be considered.

To study the nature of this anomalous trapping/detrapping mechanism, these devices were exposed to electrical stress in the presence and absence of UV light from LED source. As shown in Fig. 5, this UV exposure without any stress has also produced \( V_{TH} \) shift similar to the increase in temperature of the device. However, the shift in \( V_{TH} \) is same, after the bias stress, irrespective of presence or absence of UV light. The energy of these traps would correspond to the wavelength of UV light and the energy levels may be present from 0.9 eV to 0.5 eV below the conduction band minima.

![Graph showing measured I_D-V_G curves with and without UV at 300 K before and after the voltage stress. The shift in \( V_{TH} \) in presence of UV without an stress is comparable with curves at 450 K.](image)

IV. CONCLUSIONS

The possible trapping locations responsible for the shift in \( V_{TH} \) have been studied in this report. The simulation results show that one order higher magnitude of trap concentrations are required near the metallic gate when compared with the bulk traps in the AlGaN and GaN epitaxial layers. The physical location of the traps cannot be predicted by the simulation alone because same \( V_{TH} \) can be obtained from the trapped charges in bulk or surface states.

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REFERENCES


