Evidence of surface states for AlGaN/GaN/SiC HEMTs passivated Si_3N_4 by CDLTS

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In AlGaN/GaN heterostructure field-effect transistors (HEMTs) structures, the surface defects and dislocations may serve as trapping centers and affect the device performance via leakage current and lowfrequency noise. This work demonstrates the effect of surface passivation on the current–voltage characteristics and we report results of our investigation of the trapping characteristics of Si_3N_4-passivated AlGaN/GaN HEMTs on SiC substrates using the conductance deep levels transient spectroscopy (CDLTS) technique. From the measured of CDLTS we identified one electron trap had an activation energy of 0.31 eV it has been located in the AlGaN layer and two hole-likes traps H_1, H_2. It has been pointed out that the two hole-likes traps signals did not originate from changes in hole trap population in the channel, but reflected the changes in the electron population in the surface states of the HEMT access regions.

1. Introduction

Wide band-gap nitride semiconductors continue to attract attention as the materials for novel optoelectronic and electronic devices with applications in microwave communications, power and high-speed electronics [1–4]. In addition to their wide band-gap, excellent electronic transport properties have been achieved in nitride heterostructures using the piezoelectric enhancement mechanism. The two dimensional electron gas (2DEG) with the sheet carrier density higher than $10^{13}\,cm^{-2}$ and the room temperature mobility above $2000\,cm^2/(V\cdot s)$ can be achieved at the AlGaN/GaN interface [5,6]. GaN high-electron mobility transistors (HEMTs) have demonstrated a very high breakdown voltage and good power transfer ability [7,8].

However, the performance of the HEMTs is usually limited by trapping effects occurring both at the surface and in the bulk GaN buffer, decreasing the output current and thus output power of the device under RF operation. These point defects present in AlGaN/GaN HEMTs degrade the device performance and raise the questions for device long-term reliability. The loss of channel carriers and the resulting large transverse-electric field lead to reduced drain current and increased knee voltage [9]. Also, these effects are commonly referred to as gate- and drain-lag, respectively. Unlike the bulk defects, the activity and the number of the surface trapping centers could be partly mitigated during processing by the appropriate passivation.

Therefore much attention has been paid to the development of efficient passivating materials and processes, i. e. MgO, Sc_2O_3 [10], SiN_x [11], SiO_x [12], AlN [13], and Al_2O_3 [14]. Nevertheless, contradictory reports regarding the passivation efficiency of the same dielectric layers have been published and might origin form the different deposition processes. The use of Si_3N_4 reduces gate leakage by an order of magnitude, and hence, improves breakdown voltage and device reliability.

In this paper, in order to reduce the effects of surface traps on the barrier layer, Si_3N_4 layer passivation is utilized, which might suppress the formation of surface traps in the side-recessed region.

The aim of this work is to present results from a detailed, trap-characterization study in AlGaN/GaN HEMTs passivated Si_3N_4 and to provide a consistent interpretation for the different traps detected, both in terms of localization within the device structure and of associated charge/discharge mechanism.

2. Device structure

We fabricated high-electron mobility transistor (HEMTs) grown on silicon carbide (SiC) grown by metalorganic chemical vapor deposition (MOCVD). The AlGaN/GaN heterostructure consists of 25 nm of undoped AlGaN (25.3% Al) on $3\,\mu$m-thick undoped GaN grown on a $398\,\mu$m-thick SiC substrate. Source and drain ohmic contacts were formed by Ti/Al/Ni/Au evaporation with thicknesses of 12/200/40/100 nm and alloyed at 900°C for 30 s. TLM measurements gave a contact resistance 500 Ω. The Schottky mushroom gate was formed by Pt/Ti/Pt/Au evaporation and the subsequent lift-off process. The gate length and the gate width were 0.25 and $140\,\mu$m (with two fingers, $70\,\mu$m per finger) respectively. Following first electrical characterizations, a Si_3N_4 passivation with thickness of 2400 Å was deposited.

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3. Results and discussion

3.1. DC Characteristics

Small signal characterization was performed with a vector network analyzer HP8510 up to 40 GHz and DC measurements were made HP4142A power supply.

The electrical measurements were all performed at room temperature to avoid thermal effects on electrical traps. We have characterized 4 unpassivated devices and devices which have been passivated after the different NH_3 pre-treatments.

Fig. 1. shows a typical DC characteristic of AlGaN/GaN/SiC HEMT device and shows the influence of Si_3N_4 passivation. From these DC characteristics, we can note a shift before and after passivation whatever the knee voltage and maximum drain current. In the same figure we observed that the apparent saturation current exhibits a negative conductance at large V_{ds}. The decrease in current at higher

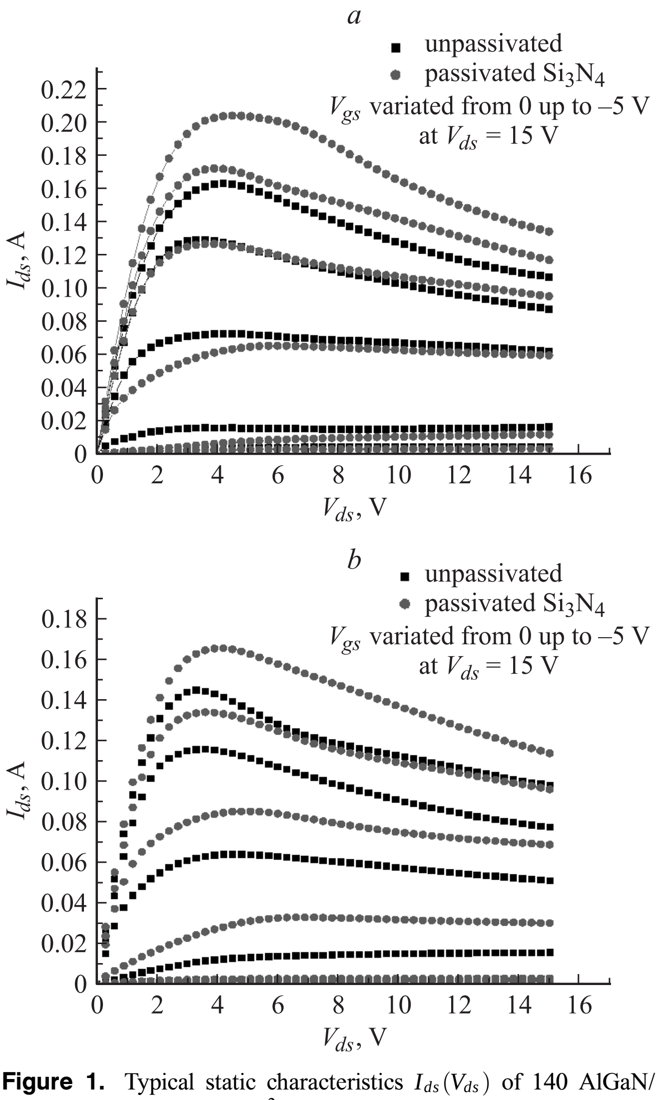

Figure 1. Typical static characteristics $I_{ds}(V_{ds})$ of 140 AlGaN/GaN/SiC HEMT $(0.25\,\mu m^2)$ before and after passivation for two transistors: *a* — 928, *b* — 125.

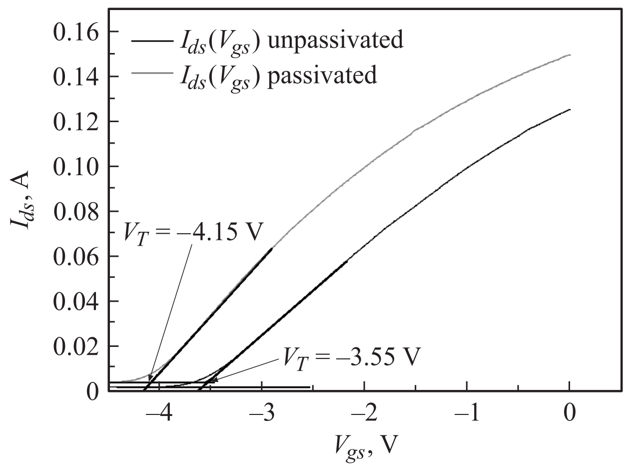

Figure 2. Transfert characteristics at $V_{ds} = 15$ V before and after passivation of 140 AlGaN/GaN/SiC HEMT $(0.25\,\mu m^2)$.

drain-source voltage is due to the self-heating and especially results in a decrease in electron mobility. In addition to self-heating, deep traps are also present in the AlGaN/GaN heterostructure and can reduce the microwave performance of designed HEMTs. Such trapping effects occur both at the surface and in bulk of the GaN epilayer. As clearly seen, for all the gate biases studied, improvements in drain current are achieved after passivation with Si_3N_4. The reason for enhanced electron transport is the increase in sheet carrier concentration. This is mainly due to the reduction in surface states. As for AlGaN/GaN HEMTs before passivation, the self-heating is also observed in DC characteristics after Si_3N_4 passivation. From this result it is not possible to locate the traps or to determine their origin. These electrical traps partially explain the poor electrical performances of the studied devices.

On the other hand, larger shifts were observed on the threshold. The threshold voltage shifted from -3.55 V to -4.15 V after passivation. This shift is shown on Fig. 2 by the transfer characteristics of the device. Therefore, we think that the shift was due to charge redistribution in the structure after passivation process.

In that case we have concluded that the electrical traps were essentially located at the surface of the HEMT. Consequently, we think that the electrical traps cannot be at the GaN/SiC interface or in the GaN volume.

However we report on in the second part an investigation performed by conductance deep level transient spectroscopy CDLTS measurements on AlGaN/GaN HEMT structures where SiN was used to either only passivate the access regions of the device.

3.2. Conductance deep level transient spectroscopy (CDLTS) measurments

Performing conductance (or current) DLTS under gate or drain pulse in correlation with capacitance deep level transient spectroscopy (DLTS) measurements improve the

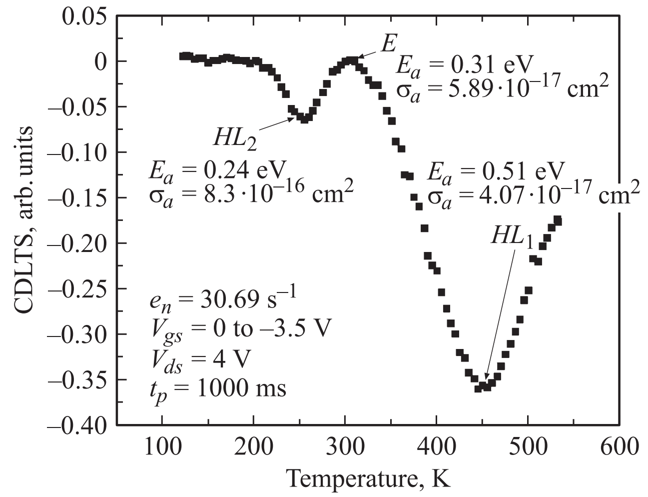

Figure 3. A typical CDLTS spectrum showing the presence of three levels E, H_1, H_2 under a gate pulse from 0 to –3.5 V at $V_{ds} = 4$ V in GaM/SiC HEMTs passivated Si_3N_4.

efficiency of trap characterisation in HEMTs. CDLTS is more suitable for the study of MODFET structure than capacitance DLTS when the gate area of such structures is too small for standard capacitance DLTS. In addition, in CDLTS, the device can be biased in reverse closer to the threshold voltage, allowing investigation of deep level in the buffer by modifying the Fermi level position in the buffer region near the channel. This is not possible with capacitance DLTS in this type of structure. Moreover, CDLTS under drain pulse allows investigation in the buffer layer and near the 2DEG.

CDLTS measurements were performed at temperature between 80 and 600 K. In Fig. 3 CDLTS spectra measured under a gate pulse on the AlGaN/GaN/SiC HEMT with a gate length of $0.25\,\mu$m reveals the presence of three peaks corresponding to hole-like from different traps called H_1, H_2 and one electron trap called E are positions at about 451, 251 and 306 K respectively. The apparent activation energies and capture cross-sections of all observed electrons traps are deduced from the Arrhenius plot of:

$$\ln\left(\frac{T^2}{e_n}\right) \quad \text{versus} \quad \frac{1000}{T}.$$

A comparison of the obtained an activation energies with the ones reported in the literature allows us to relate undoubtedly the electron trap E which appears as a shoulder at $T = 300$ K with $E_a = 0.31$ eV and capture cross-section $\sigma = 5.89 \cdot 10^{-17}\,\text{cm}^2$. Fig. 4 can be attributed to the defect level with activation energy of 0.29 eV reported by Gassoumi et al. [15] by DLTS measurements in unpassivated HEMT GaN/SiC. The very close correspondence between the Arrhenius plots for these levels and the similar activation energies derived from these plots suggest that they correspond to the same defect level. Gassoumi [16] have also observed a defect with similar signature in AlGaN/GaN/Si HEMT and have shown that this trap is located in the region below the 2DEG channel. From previous results, such a defect has been located in the AlGaN layer.

We will focus now, on the „anomalous“ hole-like traps. In order to compare the obtained activation energies with the ones reported in the literature, we notice that the origin of the hole-traps-likes H_1 and H_2 with an activation energy $E_{a1} = 0.50$ and 0.24 eV (Fig. 4), which appears as a shoulder at $T = 455$ K and 255 K respectively; to our knowledge, no data are reported in the literature concerning these traps. These defects has been detected only, in this work, by the CDLTS after gate pulses and are not found by Gassoumi el al. [15] by DLTS or CDLTS measurements in unpassivated HEMT. We believe that the hole-trap-like signals (H_1 and H_2) do not originate from changes in hole trap population in the channel, with no obvious mechanism for the injection of holes, but probably reflect the changes

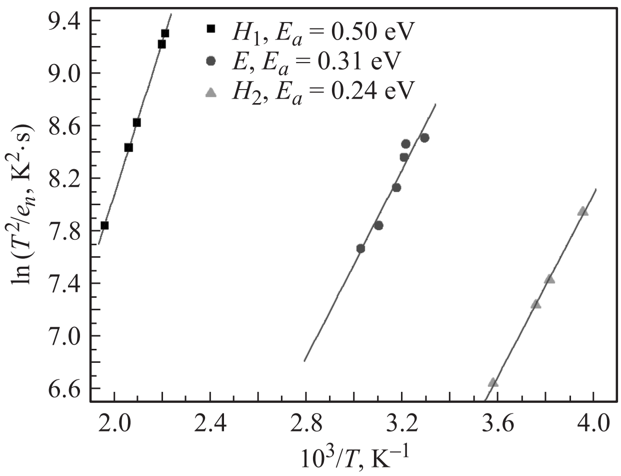

Figure 4. Arrehnius plots of the traps observed in AlGaN/GaN/SiC HEMTs passivated Si_3N_4.

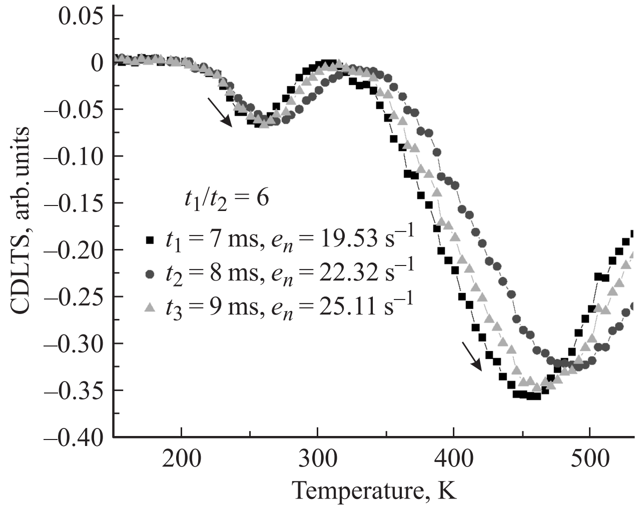

Figure 5. Conductance DLTS spectra at $V_R = 3.5$ V and for different emission rates. The arrow highlights the negative peak amplitude increasigh with temperature.

in the population of surface states in the HEMT access regions, resulting in modulation of the 2DEG density in the channel [17]. The change in the population of surface states is thought to be caused by capture and emission of the electrons injected from the gate electrode. So this seems confirm that these traps originate from surface states located at the ungated regions of the device. To strengthen the hypothesis of a capture process on surface states in the case of H_1 and H_2, we performed measurements at different emission rates (e_n). Indeed when the emission rate is changed, the peak temperature is changed also. The corresponding CDLTS spectra under a gate pulse of $V_R = 3.5\,\mathrm{V}$ is displayed in Fig. 5. We can observe on this figure that the amplitude of the peak corresponding to the capture increases with the temperature.

Also we can conclude that the changes in the occupancy of traps at the SiN semiconductor interface could be responsible for the anomalous behaviours observed in $0.25\,\mu$m HEMTs AlGaN/GaN/SiC.

4. Conclusion

The impact of Si_3N_4 passivation on AlGaN/GaN/SiC HEMT devices has been reported in this paper. DC measurements show that the device performance is dramatically enhanced after Si_3N_4 passivation. The self-heating is observed in AlGaN/GaN HEMTs after Si_3N_4 passivation as well. The results suggest that the observed improvement of device performance is related to surface states, which limit output current of the device.

Conductance DLTS was applied to the AlGaN/GaN HEMTs to study the transient behavior of the device. One positive peak (electron trap) and two hole-trap-likes were observed in the CDLTS spectrum. The electron trap had an activation energy of 0.31 eV, has been located in the AlGaN layer. It has been pointed out that the hole-trap-like signals did not originate from changes in hole-likes traps population in the channel, with no obvious mechanism for the injection of holes, but probably reflect the changes in the population of surface states in the HEMT access regions.

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