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Effect of surface passivation by SiN/SiO$_2$ of AlGaN/GaN high-electron mobility transistors on Si substrate by deep level transient spectroscopy method

© *Malek Gassoumi*[¶], *Hana Mosbahi, Mohamed Ali Zaidi, Christophe Gaquiere*[*], *Hassen Maaref*

Laboratoire de Micro-Optoélectroniques et Nanostructures,
Faculté des Sciences de Monastir, Université de Monastir,
Monastir 5000 Tunisie
[*] Institut d'Electronique de Microélectronique et de Nanotechnologie IEMN,
Département hyperfréquences et Semiconducteurs, Université des Sciences et Technologies de Lille,
59652 Villeneuve d'Ascq Cedex, France

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Device performance and defects in AlGaN/GaN high-electron mobility transistors have been correlated. The effect of SiN/SiO$_2$ passivation of the surface of AlGaN/GaN high-electron mobility transistors on Si substrates is reported on DC characteristics. Deep level transient spectroscopy (DLTS) measurements were performed on the device after the passivation by a (50/100 nm) SiN/SiO$_2$ film. The DLTS spectra from these measurements showed the existence of the same electron trap on the surface of the device.

1. Introducton

The AlGaN–GaN-based device technology is an attractive solution for the high-power operations at high-frequencies for next-generation microwave power amplifiers. GaN-based high-electron mobility transistors (HEMTs) are excellent candidates for these applications at high temperatures with minimal cooling, because of their superior physical properties such as a wide bandgap (3.4 eV), leading to high breakdown fields $2 \cdot 10^6$ V/cm and high saturation electron drift velocity 10^7 cm/s. The capability to achieve high output power densities at X-band up to K_a-band [1,2], makes the AlGaN–GaN HEMTs very interesting for the commercial and the military power applications. Nowadays, GaAs- and InP-based HEMTs are commonly used in front ends of microwave systems such as telecommunications, but there is an increasing interest to use the advantages of AlGaN–GaN HEMTs for these kind of applications in X-band. AlGaN–GaN HEMTs on Si (111) substrate present the advantages of the large scale and the availability of low cost silicon substrates.

However AlGaN–GaN HEMTs had a problem of a drain current slump during microwave operation at high-drain voltage [3]. It was suggested that the surface states in the gate-drain access region play an important role in this dispersion [4]. Surface passivation has been reported to be one solution to remove the net surface charges and reduce current slump [5]. As the power performance of AlGaN–GaN HEMTs is getting mature reliability becomes a major concern to realize the potential of these devices. Several studies on the device reliability have reported the degradation of these devices under dc and RF stress [6,7]. Typical degradation characteristics of these devices consist of a reduction in drain current, maximum transconductance ($g_{m\,\max}$) and microwave output power. Hot electron-induced degradation similar to AlGaAs–GaAs HEMTs has been observed, possibly from an induced depletion of the 2DEG from the electron trapping between the gate and drain, resulting in degradation in performance [8].

In this paper, we report the surface and defect characterizations of AlGaN/GaN wafers. A correlation of defects in the AlGaN/GaN HEMT structure and the device performance was evaluated. We found that the surface morphology induced by the dislocations directly affected the effectiveness of the SiN/SiO$_2$ surface passivation effect. The surface states and bulk defects present in AlGaN/GaN HEMTs structure strongly influenced the device power performance.

2. Sample description and experimental details

AlGaN/GaN HEMT devices used in the present letter are realized on silicon substrate. The epitaxial layers are obtained by molecular beam epitaxy (MBE) using NH$_3$ for Nitrogen precursor. The epilayer contains of AlN nucleation layer, GaN layer, 250-nm-thick of AlN layer, 2.5 μm-thick of unintentionally doped GaN buffer, 25 nm-thick of AlGaN barrier and 1-nm-thick of unintentionally doped GaN cap layer. The samples are first cleaned in acetone and isopropyl alcohol and blow-dried using N to remove the organic contaminants on the surface. The device isolation is obtained from a multiple Helium implantation at room temperature based on different energies from 20 to 190 keV and different doses. The ohmic contacts pads are patterned using ebeam lithography. Thereafter, the metallization consisting of evaporated Ti/Al/Ni/Au (12/200/40/100 nm) is deposited and followed by a rapid thermal annealing (RTA) at 900°C during 30 s under nitrogen atmosphere. In this paper, devices are passivated with SiO$_2$/SiN quickly after gate making to avoid surface oxidation.

$C-V$ measurements were carried out, at room temperature, using a PAR410 capacimeter. DLTS measurements are

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[¶] E-mail: malek.gassoumi@fsm.rnu.tn

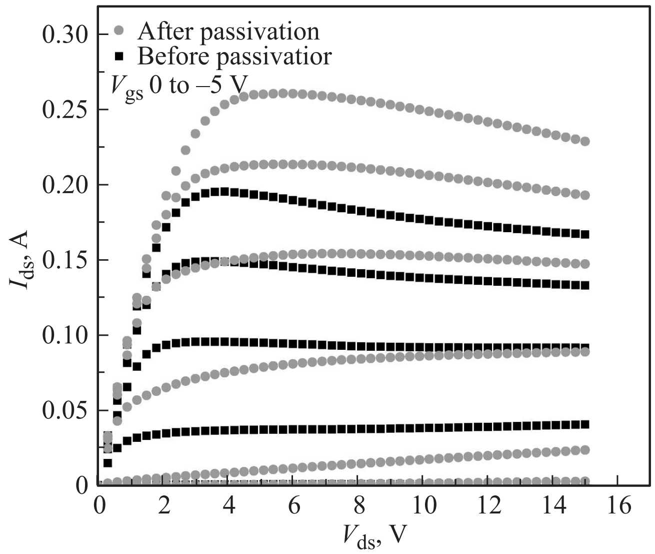

Figure 1. $I_{ds}-V_{ds}$ charcteristics of AlGaN/GaN/Si before and after passivation.

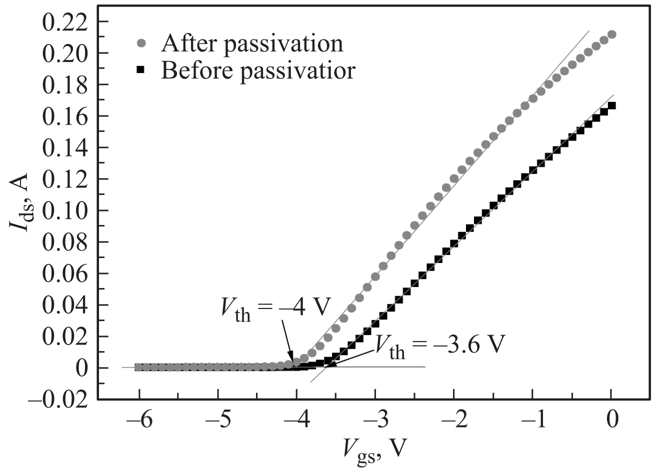

Figure 2. Transfer characteristics of AlGaN/GaN/Si before and after passivation.

performed in the temperature range 10–320 K using a He closed-cycle cryostat system.

3. Static measurements

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 6 unpassivated devices and devices which have been passivated after the different NH$_3$ pretreatments.

Fig. 1 shows a typical DC characteristic of AlGaN/GaN/Si HEMT device and shows the influence of SiN/SiO$_2$ 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 drain-source voltage is due to the self-heating and especially results in a decrease in electron mobility [9]. 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 SiN/SiO$_2$. Thereason 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 SiN/SiO$_2$ passivation.

At large V_{ds}, the saturation current, however, exhibits a negative conductance. The latter behavior is due to the self-heating and especially results from a decrease in the electron mobility. 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 -3.6 to -4 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 or is through to be a result of deep levels related to electrically active effects in the heterostructures. The origin of the various parasitic effects in the output characteristics is studied in the following using DLTS.

4. Results and discussions

4.1. $C-V$ profiling

Fig. 3, *a* shows a typical result of capacitance–voltage $(C-V)$ measurements. The data is shown in C^{-2} vs V form at top and the resulting carrier concentration as a function of voltage at bottom. This is a clear indication of the presence of a dense sheet of charge at the AlGaN/GaN heterointerface. Which we ascribe to a polarization-induced twodimensional electron gas (2DEG), just as is observed in MBE grown structures [10].

The donor profile measured by $C-V$ measurements at room temperature at on an as-grown calibration sample is shown in Fig. 3, *b*. Once again, this data shows a sheet of carriers at the AlGaN/GaN heterointerface which we ascribe to a polarization-induced twodimensional electron gas 2DEG. This is the first observation of a 2DEG in a nitride structure grown by MBE The carrier concentration decreases rapidly during the pinch-off of the 2DEG by the negative gate voltage.

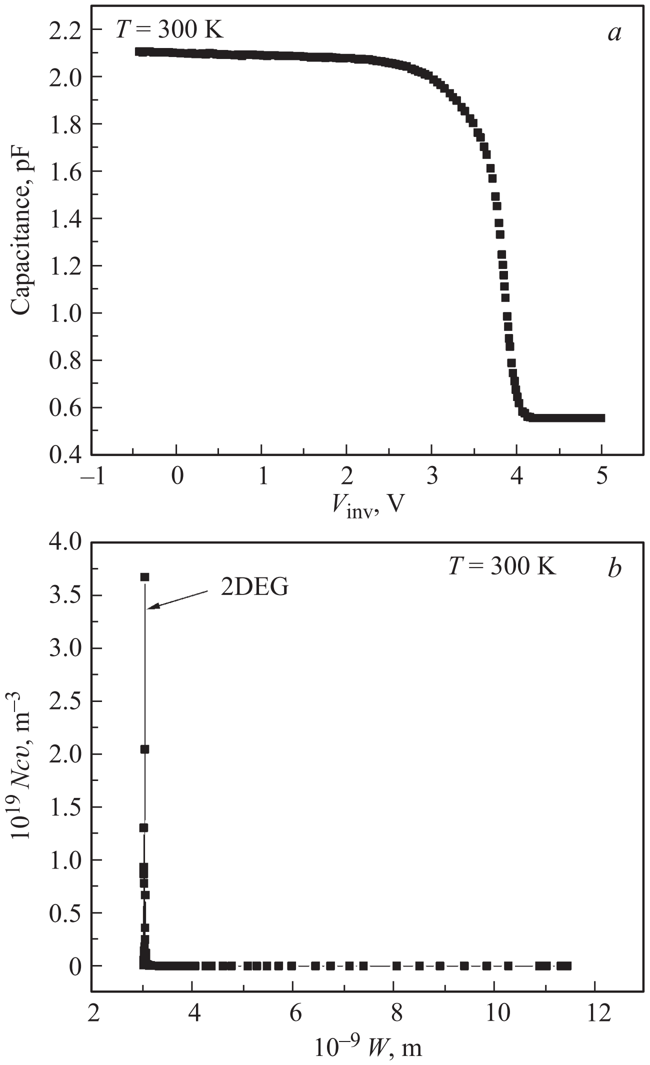

Figure 3. *a* — capacitance–voltage measurements results obtained on AlGaN/GaN/Si HEMTs at $T = 300$ K. *b* — the concentration N_{cv} versus the space charge width w.

4.2. Capacitance deep level transient spectroscopy

Undesirable phenomena such as threshold shift are hought to be caused by deep levels associated with electrically active defects in the heterostructure. To characterize deep levels in HEMT AlGaN/GaN/Si DLTS is used.

DLTS measures the capacitance or current change of a reversed biased junction when deep levels emit their carriers after they were charged by a forward bias pulse. From the temperature dependence of the emission rate, the activation energy of a deep level can be deduced. Since flicker noise in the GaN/AlGaN system is most likely related to the carrier capture and emission by some traps, we used DLTS to probe the defects.

DLTS measurements were performed at temperature between 10 and 320 K using boxcar technique. The modulation of the space charge region under the gate induced by DLTS allows investigating the traps in the barrier layer. The capacitance DLTS spectrum of the HEMT GaN/Si passivated is shown in Fig. 4 under the condition, i. e., for a bias voltage $V_0 = -3$ V a filling pulse $\Delta V = 3$ V, a filling duration $tp = 0.5$ ms, reveals the presence of one positive peak, corresponding to electron emission from different traps called $C1$, and a one negative peak corresponding to hole-like trap called with an activation energy $E_a = 0.73$ eV and 0.37 eV respectively.

The apparent activation energies and capture cross sections arededuced from the Arrhenius plot of $\ln(T^2/e_n)$ versus $1000/T$.

The Arrhenius plots of the electron traps observed in the AlGaN/GaN HEMTs on Si substrates with surface passivation SiO_2/SiN are shown in Fig. 5.

The slope of an Arrhenius plot (the electrical signature of the defect) gives an apparent ionization energy, which must be eventually corrected for the temperature variation

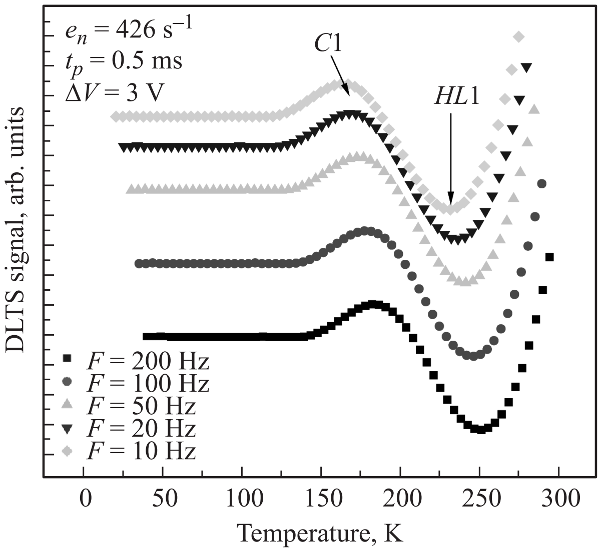

Figure 4. DLTS spectra obtained on AlGaN/GaN HEMTs on Si substrates; passivated SiO_2/SiN.

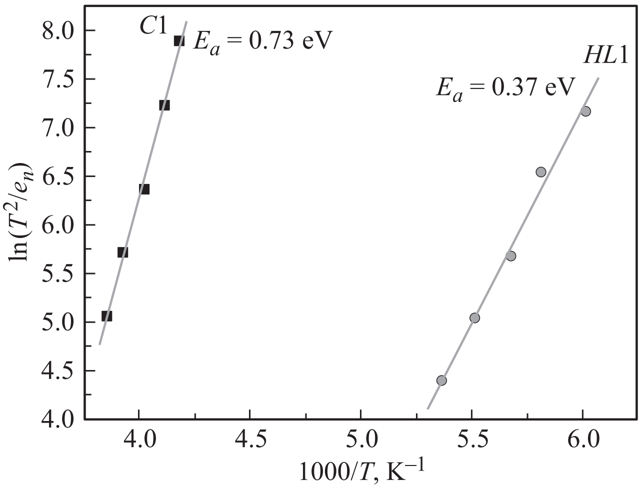

Figure 5. Arrehnius plots of the electron traps observed in AlGaN/GaN/Si HEMTs.

of the cross section s to obtain the true energy level of the trap [11,12].

In order to compare the obtained activation energies with the ones reported in the literature, we notice that the origin of the trap C_1, which appears as a shoulder at $T = 260\,\text{K}$ with $E_a = 0.73\text{eV}$ and capture cross section $\sigma_n = 1.72 \cdot 10^{-9}\,\text{cm}^2$. A center with such energy is often observed in the AlGaN/GaN structures and GaN, and is indeed related to point defects localized near dislocations [13]. In [14], simulation of the data obtained by high-resolution electron microscopy was carried out and it was shown that a new type of dislocations with no dangling bonds exists in GaN. Such dislocations are electrically inactive. However, as was shown by the authors [14], due to high local stresses in combination with a small lattice constant of these material, deep-level centers should emerge near dislocations.

Despite the exact microscopic nature of level C_1 which cannot be undoubtedly established, the interesting point is that we can conclude that this level is located either in the surface between gate and drain on in the volume near the 2DEG.

The hole trap $HL1$ with activation energy 0.37 eV and capture section $\sigma_n = 3.23 \cdot 10^{-13}\,\text{cm}^2$ peaked at $T = 250\,\text{K}$, was observed, has been investigated by Gassoumi et al. [15], using CDLTS under gate pulse on the AlGaN/GaN/SiC HEMTs. They suggested that this centre is the deep acceptor responsible for the donor-acceptor pair and yellow luminescence band in GaN.

We believe that the hole-trap-like signals ($HL1$) 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 in the population of surface states in the HEMT access regions, resulting in modulation of the 2DEG density in the channel [9]. 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.

5. Conclusion

In summary, the impact of SiN/SiO$_2$ passivation on AlGaN/GaN/Si HEMT devices has been reported in this paper. DC measurements show that the device performance is dramatically enhanced after SiN/SiO$_2$ passivation. The self-heating is observed in AlGaN/GaN HEMTs after SiN/SiO$_2$ passivation as well. At large V_{ds}, the saturation current, however, exhibits a negative conductance. Also, the mobility decrease for a high value of V_{ds} at function of temperature, this behavior is due to the existance of Self-heating.

The results suggest that the observed improvement of device performance is related to surface states, which limit output current of the device.

An investigation of the traps in passivated AlGaN/GaN HEMT transistors on Si substrate SiO$_2$/SiN, by means of capacitance transient spectroscopy, was performed; reveals two traps with an activation energy respectively 0.73 and 0.37 eV. These traps are located in the surface between gate-drain in the volume and near the 2DEG. The existence of traps even in passivated devices showed that the passivation process must be optimized to obtain the best RF power performance.

References

[1] Y.F. Wu, B.P. Keller, S. Keller, D. Kapolnek, S.P. Denbaars, U.K. Mishr. IEEE Electron. Dev. Lett., 586 (2001).

[2] C. Lee, H. Wang, J. Yang, L. Witkowski, M. Muir, M.A. Khan, P. Saunier. Electron. Lett., 924 (2002).

[3] E. Kohn, I. Daumiller, P. Schmid, N.X. Nguyen, C.N. Nguyen. Electron. Lett., 1022 (1999).

[4] R. Veturi, N.Q. Zhang, S. Keller, U.K. Mishra. IEEE Trans. Electron. Dev., 560 (2001).

[5] B.M. Green, K.K. Chu, E.M. Chumbes, J.A. Smart, J.R. Shealy, L.F. Eastman. IEEE Electron. Dev. Lett., 268 (2000).

[6] Y. Liu, J.A. Bardwell, S.P. McAlister, H. Tang, J.B. Webb, T.W. MacElwee. Phys. Status Solidi A, **188**, 233 (2001).

[7] C. Lee, L. Witkowski, M. Muir, H.Q. Tsering, P. Saunier, H. Wang, J. Yang, M.A. Khan. In: *Proc. Lester Eastman Conf. High Performance Devices* (Newark, DE, 2002).

[8] H. Kim, V. Tilak, B.M. Green, J.A. Smart, W.J. Schaff, J.R. Shealy, L.F. Eastman. Phys. Status Solidi A, **188**, 203 (2001).

[9] M. Gassoumi, B. Grimbert, C. Gaquiere, H. Maaref. Semiconductors, **46**, 382 (2012).

[10] J.C. Zolper. Tech. Dig. IEDM 16.1.1, 389 (1999).

[11] M. Zazoui, S.L. Feng, J.C. Bourgoin. Semicond. Sci. Techn., **6**, 973 (1991).

[12] J. Criado, A.I. Gomez, E. Calleja, E. Munoz. Appl. Phys. Lett., **52**, 660 (1988).

[13] A. Hierro, A.R. Arehart, B. Heying. Phys. Status Solidi B, **228**, 309 (2001).

[14] L. Lymperakis, J. Neugebauer, M. Albrecht. Phys. Rev. Lett., **93**, 196 401 (2004).

[15] M. Gassoumi. J. Optoelectron. Adv. Mater., **11**, 1713 (2009).

Редактор Т.А. Полянская