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DC and microwave performance of AlGaN/GaN HEMTs passivated with sputtered SiN$_x$

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Abstract
The effects of sputtered and room temperature plasma enhanced chemical vapour deposition (RT-PECVD) SiN$_x$ passivation on the dc and microwave performance of AlGaN/GaN high electron mobility transistors (HEMTs) are studied. The pulsed *I*–*V* characteristics from a class B quiescent bias point and transient measurements indicate that the sputtered SiN$_x$ passivation is more efficient in suppressing lag effects in AlGaN/GaN HEMTs. Dispersion-free sputtered SiN$_x$ passivated AlGaN/GaN HEMTs were obtained using this technique. Continuous-wave (CW) measurements without active cooling give a maximum output power density of 6.6 W mm^{-1} at $V_{gs} = -4$ V, $V_{ds} = 50$ V and a maximum power added efficiency of 51.3% at $V_{gs} = -4$ V, $V_{ds} = 30$ V at 3 GHz on 2 × 50 μm AlGaN/GaN HEMTs on the sapphire substrate, with a gate length of 2 μm and without field-plated gates. To the best of our knowledge, this is the highest level power density reported on the sapphire substrate without field-plate design. The extrinsic cut-off frequency (f_t) and maximum oscillation frequency (f_{max}) are 51 GHz and 100 GHz, respectively, on 2 × 50 × 0.15 μm HEMTs. To our knowledge, the sputtered SiN$_x$ passivation for AlGaN/GaN HEMTs is a unique technique, which has never been published before.

1. Introduction

GaN based field-effect transistors (FETs) have attracted considerable attention due to their excellent performance for microwave, high power and high temperature applications. In particular, the AlGaN/GaN heterostructure is technologically interesting since it combines the excellent III-nitrides material properties and a considerable spontaneous and piezoelectric polarization inducing charging of the 2DEG formed at the interface [1], making it suitable for the realization of high electron mobility transistors (HEMTs) for high power and high frequency operation [2–4]. However, this polarization mechanism also introduces the surface trapping state problems which result in current slump problems, limiting the microwave power performance of the device [5, 6].

The performance of the AlGaN/GaN HEMTs is often limited by trapping effects occurring either both at the AlGaN layer and surface or in bulk GaN epitaxial layers [5, 6]. Unlike the bulk defects, the activity and number of the surface trapping centres could be mitigated during processing by appropriate device passivation. Consequently, much research has been devoted lately to the development of efficient passivation

Table 1. Description of samples (process splits and parameters).

Name	Material no.	Passivation	Gate length (μm)	Source–drain spacing (μm)
Sample 1	1	Sputtered	2	10
Sample 2	1	PECVD	2	10
Sample 3	2	Sputtered	2 and 0.15	10 and 2

materials and processes, e.g. MgO, Al_2O_3, SiN_x AlN and SiO_2 [7–13]. Binari *et al*, in a first systematic investigation, demonstrated that the presence of traps at the surface explains the gate-lag problem seen in the gate recovery transient measurement [5]. They also showed that no passivation would result in current collapse, since the trapping sites are not eliminated at the surface or AlGaN Schottky layer [5]. Similar experimental results can also be found in several passivation investigations [7–10].

In this work, sputtered and PECVD deposited silicon nitride (SiN_x), two intrinsic different process techniques were studied for passivation of AlGaN/GaN HEMTs. We use the transient measurement technique (the gate voltage is stepped from V_{pinch} to 0 V at a given constant drain bias and resulting transient drain current is monitored) to quantify the surface state with different passivation techniques. The sputtered SiN_x passivation is a unique technique to AlGaN/GaN HEMTs, which has never been published in the literature before. The suitability of these passivation layers was investigated by dc, pulsed *I–V*, transient and load pull measurements. The main focus of this paper is on the sputtered physical vapour deposition SiN_x passivation AlGaN/GaN HEMT performance and the relations between pulsed *I–V* and power measurement results. The comparison of the chemical vapour deposition and physical vapour deposition SiN_x passivation AlGaN/GaN HEMT performance is also demonstrated.

2. Experiment

The AlGaN/GaN heterostructures were grown on a sapphire by metal–organic chemical–vapour deposition (MOCVD) by RF Micro Devices Inc. (material 1) and NTT Basic Research Labs (material 2). They consisted of a 2 μm thick, unintentionally doped GaN buffer layer followed by undoped 25 nm and 30 nm $Al_{0.3}Ga_{0.7}N$ on materials 1 and 2, respectively. The sheet carrier concentration and electron mobility determined by Hall measurements were 9×10^{12} cm^{-2} and 900 cm^2 (V s)$^{-1}$, and 1×10^{13} cm^{-2} and 1100 cm^2 (V s)$^{-1}$ on materials 1 and 2, respectively.

The HEMTs were then fabricated using an in-house process at Chalmers University. The epiwafers were first cleaned using a standard degreasing procedure and standard RCA cleaning. The mesas were etched by chorine based inductively coupled plasma reactive ion etching (ICP-RIE). Ohmic contacts for the source and drain were formed by e-beam evaporation of a Ti/Al/Ni/Au multilayer followed by rapid thermal annealing (RTA) in a nitrogen environment at 800 °C. A typical contact resistance of 0.2 Ω mm was measured on the chip using TLM patterns. In this study, three samples were used and their variables are summarized in table 1.

The $2 \times 50 \times 2$ μm^2 gates were defined in the middle of the 10 μm source–drain spacing on all samples. The $2 \times 50 \times 0.15$ μm^2 gates were defined in the 2 μm source–drain spacing on the chip of material 2 (sample 3). The Ni/Au gate metallization was deposited by e-beam evaporation. The chips were later passivated by two differently processed, 80 nm thick SiN_x layers. One piece of material 1 (sample 1) and one piece of material 2 (sample 3) were passivated with an optimized sputtering process with a Si target and constant N_2/Ar (8/30 sccm) gas flow in the sputter system (Balzer PLS 550). The other sample of material 1 (sample 2) was passivated with a PECVD process with constant SiH_4/N_2/Ar (8/20/50 sccm) gas flow in the Oxford PECVD system. The refractive indices of the two different SiN_x films were both measured to be 2.04 (with Woolam M2000 ellipsometer at a wavelength of 634 nm). Finally, the dielectric layer was opened on the probing pads with a fluorine-based RIE process.

3. Results and discussion

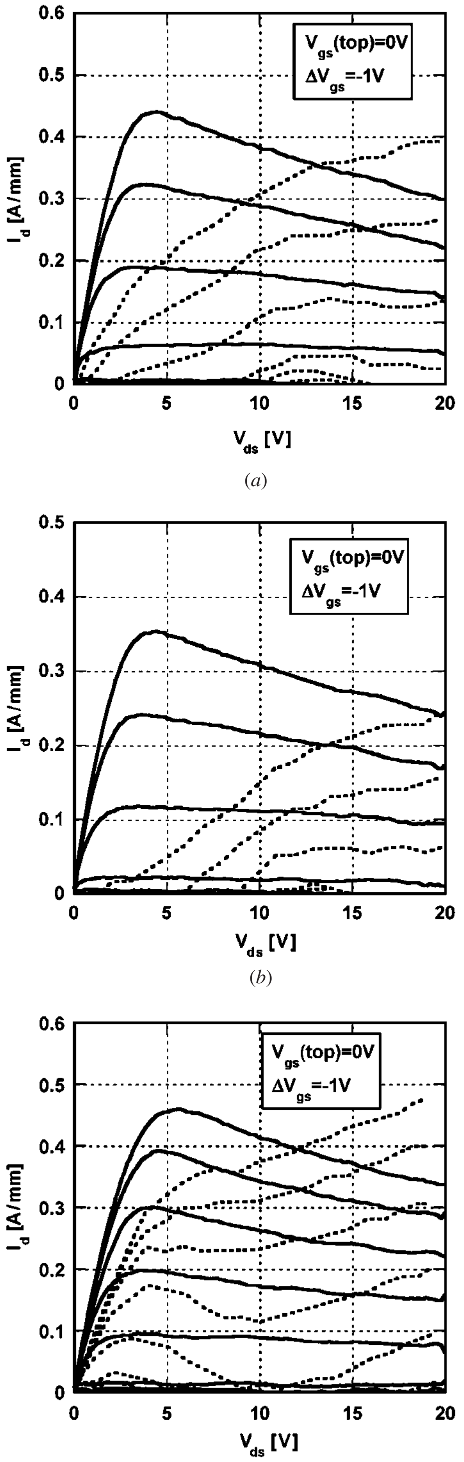
3.1. Pulsed I–V characteristics

In order to investigate the trapping of electrons in the epi-structures and surface, the dynamic properties of the HEMTs were evaluated using a pulsed *I–V* system (Accent DiVA D225) [14, 15]. Comparing the dc and pulsed *I–V* characteristics of the HEMTs is a very useful way to check the charge trapping problems introducing gate- and drain-lag phenomena in semiconductor devices. The choice of pulse width is very important in the dynamic pulsed measurement study and revealed very different results [16]. Normally, a pulse width of 100 ns to 1 ms is suitable to investigate the trapping problems in semiconductors with sufficient accuracy in the current measurement. In this time region, the shorter pulse time is more efficient to remove the channel self-seating problem and also more efficient to reveal the trapping phenomenon [16].

In this study, a pulse width of 100 ns (the limitation of the instrument) and 0.1% duty cycle were applied to investigate the lag problems in the AlGaN/GaN HEMTs. Figure 1 shows two different measurements: the dc, and the pulsed from $V_{\text{gs}} = V_{\text{pinch}}$, $V_{\text{ds}} = 20$ V (a class B operation bias). The class B bias point is an effective way to clarify the gate-lag and drain-lag effects at the same time [14, 15]. Less current collapse was observed in the HEMTs with sputtered SiN_x passivation (sample 1) (figure 1(*a*)) compared to the PECVD passivation (sample 2) (figure 1(*b*)). These results indicate that the sputtered SiN_x passivation has a better surface charge trapping recovery efficiency compared to the PECVD SiN_x used in this work. We can distinguish the improvement in surface passivation, since the trapping states in the GaN bulk layer should be the same for samples 1 and 2 (both from material 1). For sample 3 (figure 1(*c*)), there was almost no current collapse problem. These results indicate that material 2 has better surface and AlGaN Schottky layer quality and fewer trapping states in the GaN buffer layer.

3.2. Transient characteristics

Gate lag is attributed to surface states acting as electron traps located in the un-gated areas between gate and drain [5, 16].

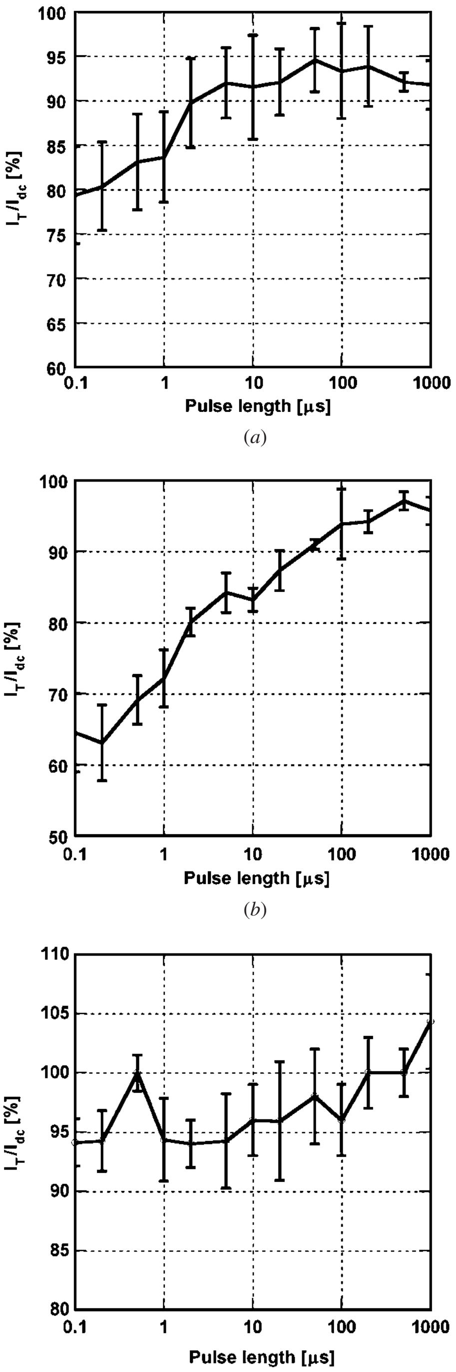


(a)

(b)

(c)

Figure 1. DC (solid line) and pulsed (dashed line) *I–V* characteristics of the sputtered (sample 1) (*a*), the PECVD SiN$_x$ passivated HEMTs (sample 2) (*b*) and sputtered SiN$_x$ passivated HEMTs (sample 3) (*c*).



(a)

(b)

(c)

Figure 2. Transient characteristics of AlGaN/GaN HEMTs at $V_{ds} = 3$ V with different passivations: sample 1 (*a*), sample 2 (*b*) and sample 3 (*c*).

Transient measurements (with Accent DiVA D225 [15]), i.e. stepping the gate voltage from V_{pinch} to 0 V at a given constant drain bias and monitoring the resulting transient drain current, I_T, is one way of investigating these states. Figure 2 shows current recovery, defined as the ratio of the transient drain current (I_T) and the dc current (I_{dc}). More than five devices were measured to generate the error bars in figure 2. The current recovery (I_T/I_{dc}) for the sputtered passivation devices in figure 2(*a*) shows a much shorter time constant compared to the PECVD passivation devices in figure 2(*b*), i.e. the sputtered SiN$_x$ passivation technique shows better elimination efficiency of surface charge trapping effect. Figure 2(*c*) shows a very good current recovery for material 2, revealing the difference of the different epi-wafers. This shows that both the surface passivation process (comparing samples 1 and 2) and the epi-growth (comparing samples 2 and 3) affect the gate lag. Nevertheless, the obvious difference shown in figures 2(*a*) and (*b*) still provides clear evidence that the proper passivation process can apparently reduce the gate-lag problems in the devices even in the material suffering from surface trapping effects.

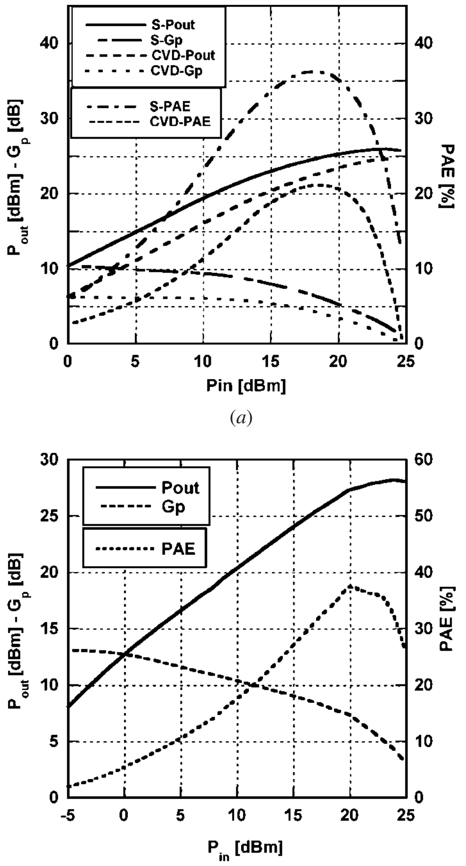
3.3. RF performance

The large signal performance of the devices was evaluated by CW load pull measurements at 3 GHz without active cooling. The measurements are summarized in table 2 and shown in figure 3.

Table 2. Comparison of large signal performance at 3 GHz.

Name	$P_{\max}$ (W mm^{-1})	PAE (%)	Passivation	Gate length (μm)	Figure
Sample 1	4.0^{a}	36^{a}	Sputtered	2	3(*a*)
Sample 2	3.1^{a}	21^{a}	PECVD	2	3(*a*)
Sample 3	6.6^{b}	51^{a}	Sputtered	2	3(*b*)

[a] $V_{ds} = 30$ V.
[b] $V_{ds} = 50$ V.



(*a*)

(*b*)

Figure 3. Power sweep of AlGaN/GaN HEMTs with sputtered (*S*) (sample 1) and PECVD (CVD) (sample 2) SiN$_x$ passivation at $V_{ds} = 30$ V and $V_{gs} = -3$ V (*a*) and sputtered SiN$_x$ passivated AlGaN/GaN HEMTs at $V_{ds} = 50$ V and $V_{gs} = -4$ V (*b*).

These measurements show that the HEMTs passivated by sputtered SiN$_x$ have better large signal performance. These results are in accordance with the different trapping effects revealed by the pulsed and transient measurements (figure 2).

The $2 \times 50 \times 0.15$ μm gate devices exhibited an extrinsic cut-off frequency (f_t) and maximum oscillation frequency ($f_{\max}$) of 51 GHz and 100 GHz, respectively, calculated from *s*-parameters measured up to 50 GHz. These results show that the sputtered SiN$_x$ passivation is also suitable for the high frequency application.

4. Conclusion

Sputtered and PECVD SiN$_x$ passivations for AlGaN/GaN HEMTs were investigated. The output power density and power added efficiency could be directly correlated to the gate- and drain-lag characteristics of the different passivations. The sputtered SiN$_x$ passivation was shown to be a good candidate for passivation of microwave power AlGaN/GaN HEMTs, since it efficiently reduced the surface trapping effect on the AlGaN/GaN HEMTs. To our knowledge, the sputtered SiN$_x$ passivation for AlGaN/GaN HEMTs is a unique technique, which has never been published in the literature before.

AlGaN/GaN HEMTs grown on a sapphire, without field plate and sputtered SiN$_x$ passivation have a maximum output power density of 6.6 W mm^{-1} and a maximum PAE of 51.5%.

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