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# Evaluation of the electrical properties of ScAlN/GaN HEMTs grown by ammonia source molecular beam epitaxy

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## Abstract

In this work, the electrical properties of ScAlN/GaN high electron mobility transistor (HEMT) heterostructures grown by ammonia source molecular beam epitaxy are studied. The effect of growth temperature and ScAlN barrier thickness on 2DEG carrier density is investigated with capacitance-voltage measurements. Alloyed ohmic contacts have been developed to evaluate the electron mobility and a first functional transistor is demonstrated.

## Introduction

ScAlN is a wide bandgap material with very large piezoelectric and spontaneous polarization coefficients [1-2] which ensures a very high charge density at the interface between ScAlN and GaN [3]. Moreover,  $\text{Sc}_x\text{Al}_{1-x}\text{N}$  alloy with  $x=0.18$  can be grown strain-free (lattice-matched) on GaN, as InAlN barrier layer [4], but with much higher sheet electron concentration at the interface [3]. Thus, ScAlN is currently a promising barrier layer candidate to build the next generation of high-frequency and high-power high electron mobility transistors (HEMTs) [3,5]. For that purpose, the epitaxial growth of ScAlN has been developed recently by few groups using plasma-assisted molecular beam epitaxy (PA-MBE) [6-7]. The growth of ScAlN using metal-organic chemical vapor deposition (MOCVD) is challenging due to the crucial choice of the precursors and the need to “rebuild” the reactor to allow Sc incorporation into AlN [8-10]. Therefore, the first ScAlN/GaN heterostructures grown by MOCVD has been only published in 2020 [8-9]. Despite its very recent history, the epitaxial growth of ScAlN alloy has already allowed the demonstration of high-performances RF-HEMTs [11-12]. Previous studies on AlGaIn/GaN RF-HEMTs obtained by ammonia-source MBE ( $\text{NH}_3$ -MBE) allowed to reach high performances [13-14] but in spite of few papers reporting on ScGaN [15], there is no report about ScAlN grown by this technique up to now. In this letter, the electrical properties of ScAlN/GaN heterostructures grown by  $\text{NH}_3$ -MBE is studied for the first time. The effect of growth temperature and barrier thickness on the density of the two-dimensional gas (2DEG) is investigated as well as the electron mobility in heterostructures grown on Silicon substrate. Finally, the fabrication of annealed ohmic contact is investigated and a functional transistor is demonstrated.

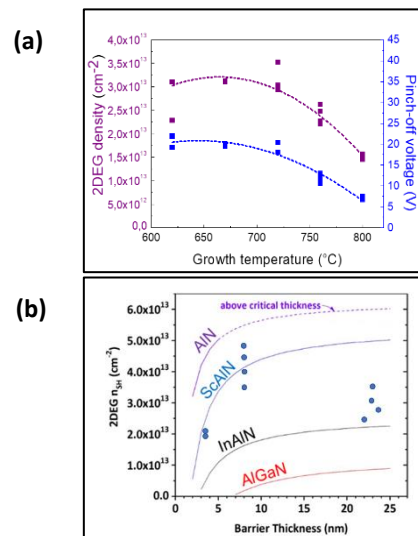
## Experimental

The HEMT structures were grown in a Riber Compact 21T reactor. A 200 sccm  $\text{NH}_3$  flow rate was used to maintain nitrogen-rich growth conditions [16]. The Sc content in the alloy was investigated using X-ray photoelectron spectroscopy and X-ray diffraction. Contents varied between 16% and 14% depending on the growth temperature which was between 620°C and 800°C [17]. The studied heterostructures consist of 5-25 nm nominal thickness ScAlN barriers grown with a 1 nm AlN exclusion layer on GaN. The capacitance was extracted using a 4284A Agilent LCR meter connected to a mercury probe. Standard photolithography lift-off was used to define ohmic contacts based on electron beam evaporated Ti, Al, Ni and Au and Schottky contacts based on Ni and Au. The test device patterns were isolated by chlorine based

reactive ion etching. DC I-V and Hall effect measurements were performed on-wafer with a probe station adapted for this purpose.

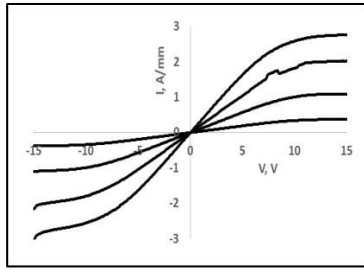
## Results and Discussion

**Fig.1.a** reminds the dependence of the 2DEG carrier density and pinch-off voltage with the growth temperature for heterostructures regrown on 2 in. MOCVD GaN-on-sapphire templates. Both parameters deduced from capacitance-voltage measurements are correlated and do not vary significantly below 720°C. The 2DEG density is around  $3 \times 10^{13}/\text{cm}^2$  and decreases beyond this growth temperature. However, an increase to about  $4 \times 10^{13}/\text{cm}^2$  is noticed while reducing the nominal ScAlN thickness to 10 nm (**Fig.1.b**), which may indicate a better crystal quality for thinner material. Finally, a carrier density of  $2 \times 10^{13}/\text{cm}^2$  for 5 nm nominal thickness is obtained. Considering the barrier thickness reduction due to the generation of a 2 nm thick oxide layer, these densities agree quite well with expected values [3].



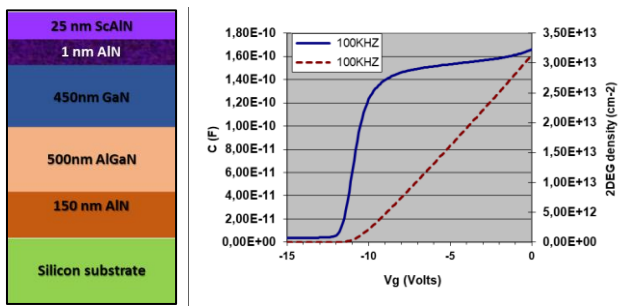
**Fig.1.a.** 2DEG density and pinch-off voltage as a function of the growth temperature for 25 nm ScAlN barrier HEMTs. **b.** 2DEG density as a function of ScAlN barrier thickness (adapted from [3]).

The first attempts to fabricate Ti/Al/Ni/Au ohmic contacts with a process previously developed for AlGaIn/GaN HEMTs failed. Indeed, in spite of rapid thermal annealing at temperatures ranging from 800°C to 875°C, non-linear I-V characteristics were obtained at low bias. Nevertheless, as shown in **Fig.2**, a second annealing step at 925°C resulted in ohmic behaviours with contact resistances below 0.2 ohm.mm and very large saturation currents, up to 2.6 A/mm for a contact spacing of 5  $\mu\text{m}$ .



**Fig. 2.** I-V measurements performed on TLM patterns with contact spacings of 5/10/15/20  $\mu\text{m}$  fabricated on a 25 nm ScAlN barrier HEMT grown on a GaN-on-Sapphire template.

In a similar way, the first trials on the ScAlN/GaN HEMT heterostructure grown on silicon substrate shown in **Fig.3** produced large contact resistances (superior to 10 ohm.mm) and a second annealing step at 800°C enabled to reach less than 2 ohm.mm for some parts of the sample. Despite these large resistances, electrical test devices can provide fruitful information.

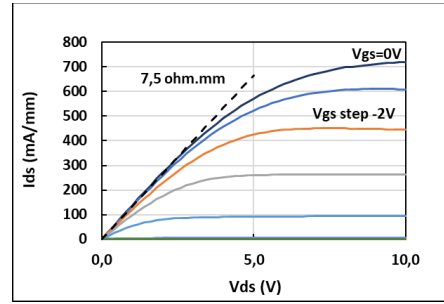


**Fig. 3.** Cross section view of the ScAlN/GaN HEMT grown on silicon substrate and C-V performed on a 200  $\mu\text{m}$  diameter circular diode.

C-V measurements performed on large diameter Schottky diodes confirm the presence of a 2DEG with the density previously obtained with the mercury probe (**Fig.3**). Furthermore, the sheet resistance of the 2DEG ranges between 350 ohm/sq and 380 ohm/sq as revealed by measurements on Van der Pauw patterns performed after the first annealing step (**Table 1**). In this case, the sheet carrier concentration ranges between  $2.6 \times 10^{13}/\text{cm}^2$  and  $3.9 \times 10^{13}/\text{cm}^2$  while the mobility is generally around  $620 \text{ cm}^2/\text{V.s}$ . On the other hand, the second annealing step produced an increase of the sheet resistance mainly attributed to the reduction of the 2DEG carrier concentration between  $2.0 \times 10^{13}/\text{cm}^2$  and  $2.3 \times 10^{13}/\text{cm}^2$ . Despite this degradation and still large contact resistances, transistors with interesting DC output characteristics could be measured. A saturated drain current as high as  $I_{ds}=700 \text{ mA/mm}$  at  $V_{gs}=0\text{V}$  and a total on-resistance  $R_{on}=7.5 \text{ Ohm.mm}$  have been achieved in a transistor with a 2.8  $\mu\text{m}$  gate and 7.8  $\mu\text{m}$  source-drain spacing (**Fig.4**). The maximum transconductance at  $V_{ds}=10 \text{ V}$  is around 90 mS/mm and the pinch-off voltage  $V_{gs} \sim -10\text{V}$ .

	1st anneal			2nd anneal		
	Rsh (ohm/sq)	Nh (/cm <sup>2</sup> )	$\mu\text{h}$ (cm <sup>2</sup> /V.s)	Rsh (ohm/sq)	Nh (/cm <sup>2</sup> )	$\mu\text{h}$ (cm <sup>2</sup> /V.s)
ptc1215						
H11				518	$2,32\text{E}+13$	519
H12	351			519	$2,29\text{E}+13$	525
H13				527	$2,25\text{E}+13$	527
H12	362			609	$2,00\text{E}+13$	514
ptc1215-2						
I10	374	$2,64\text{E}+13$	632			
I11	360	$2,77\text{E}+13$	627			
J10	349	$2,86\text{E}+13$	626			
J11	347	$3,92\text{E}+13$	617			
K11	358	$3,01\text{E}+13$	580			

**Table 1.** Sheet resistance, carrier density and electron mobility measured by Hall effect on the ScAlN/GaN HEMT grown on silicon substrate.



**Fig. 4.** DC output characteristics  $I_{ds}(V_{ds}, V_{gs})$  of a 2.8  $\mu\text{m}$  gate transistor with 7.8  $\mu\text{m}$  source-drain spacing fabricated on the ScAlN/GaN HEMT grown on silicon.

### Conclusions

In this work, the electrical properties of ScAlN/GaN HEMTs grown by ammonia source molecular beam epitaxy have been studied. Low-resistance ohmic contacts achieved after high temperature annealing allowed to demonstrate current densities up to 2.6 A/mm on samples initially showing a 2DEG with a carrier density of  $3 \times 10^{13}/\text{cm}^2$  on GaN-on-sapphire templates. On the other hand, a first HEMT grown on silicon substrate with similar 2DEG density exhibited a sheet resistance as low as 350 ohm/sq. Despite high contact resistances and a degradation of the sheet resistance after a second annealing step, a transistor with a 2.8  $\mu\text{m}$  gate and 7.8  $\mu\text{m}$  source-drain spacing exhibits a total on-resistance  $R_{on}=7.5 \text{ Ohm.mm}$ . This is very encouraging, considering that the heterostructure is not passivated and optimizations of the growth of ScAlN are still under way.

### Acknowledgments

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