AlInN/GaN HEMTs on SiC and on Silicon with Regrown Ohmic Contacts by Selective Ammonia MBE

Stefano Tirelli[1], Diego Marti[1], Lorenzo Lugani[2], Marco Malinverni[2], Étienne Giraud[2], Jean-François Carlin[2], Nicolas Grandjean[2] and C. R. Bolognesi[1]*

[1]Millimeter-Wave Electronics Group, ETH-Zürich, Gloriastrasse 35, Zürich 8092, Switzerland
[2]LASPE, EPFL, Lausanne 1015, Switzerland.
*E-Mail: colombo@ieee.org, Telephone: +41 44 632 87 75

Keywords: Ohmic contacts, Epitaxial regrowth, mm-wave HEMTs

Abstract

Low-resistance Ohmic contacts are fundamental performance enablers in millimeter-wave wide bandgap GaN-based HEMTs. Whereas contacts to conventional AlGaN/GaN HEMTs can already prove challenging, the higher Aluminum content and wider bandgaps of AlInN or AlN barriers pose an even greater manufacturing challenge to achieving repeatable low-resistance Ohmic contacts. We report the realization of 50 or 100 nm T-gate AlInN/GaN HEMTs on semi-insulating SiC and high-resistivity Silicon (HR-Si) substrates with regrown Ohmic contacts produced by selective ammonia MBE. Devices on both substrate types show high current gain cutoff frequencies f_T and excellent maximum oscillation frequencies $f_{MAX} > 220$ GHz and promising large-signal properties in W-band (94 GHz) with power output levels > 1.3 W/mm.

INTRODUCTION

Low resistance Ohmic contacts are of primordial importance to the realization of short gate length HEMTs as shown by the classic work of Hughes and Tasker for AlGaAs/GaInAs HEMTs [1]. The important impact of Ohmic contacts in GaN HEMTs was pointed out by DiSanto et al. [2, 3] who first clarified how much faster GaN HEMTs could be achieved if Ohmic contacts could be improved. Perhaps the best demonstration of this line of thought was given in the work of Shinohara et al. who achieved cutoff frequencies f_T/f_{MAX} = 450/440 GHz in completely self-aligned AlN/GaN HEMTs with regrown Ohmic contacts [4].

High-Aluminum content barriers such as AlN or AlInN present a more serious challenge to the formation of low-resistance annealed Ti/Au/Al- based Ohmic contacts. In our laboratory, annealed Ohmics with resistances as low as 0.3 Ω·mm have been achieved but with a rather poor level of repeatability: it is typical for our annealed Ohmic contacts on AlInN/GaN HEMTs to show resistance levels of 0.5 – 1.0 Ω·mm which would mask the performance of an otherwise excellent device or circuit.

Fig. 1 below shows a crosss-section through an annealed contact on a GaN HEMT epilayer: one clearly sees inhomogeneities between the metallization and the epitaxial material. Fig. 2 shows a focused ion beam cut through a contact with energy dispersion x-ray (EDX) compositional analysis: the metallization stack elements the redistribute non-evenly, and this is probably related to the rather wide spread in measured contact resistances one can experience. Extensive experimental work in our laboratory failed to yield a satisfactorily stable low-resistance annealed contact process on AlInN/GaN HEMTs. This observation pushed us to consider contact regrowth in order to achieve reproducible low-resistance Ohmics on AlInN/GaN HEMTs grown on various platforms.

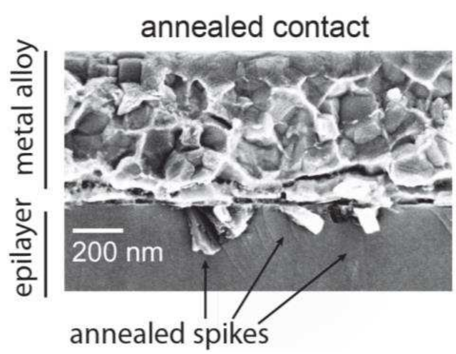

Figure 1. Cross-sectional SEM image of an annealed Ti/Al/Mo/Au Ohmic contact on a GaN 2DEG sample. The contact area between the metal stack and the epitaxial layer is clearly non-uniform.

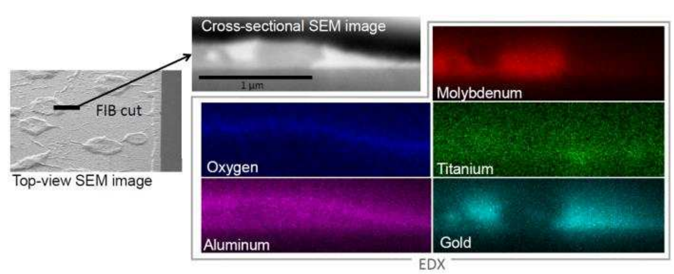

Figure 2. Scanning electron microscope image (left) and focused ion beam cut and EDX analysis through a Ti/Al/Mo/Au contact annealed at 850°C. Not all elements redistribute evenly.

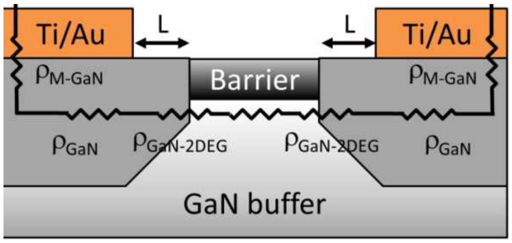

Figure 3. Regrowth of n+ GaN and resulting contact resistance contributions.

In the present work, we studied the realization of non-self-aligned regrown n+ Ohmic contacts in AlInN/GaN HEMTs grown on both SiC and high-resistivity Silicon (HR-Si). For a gate length of $L_G = 50$ nm, regrown contact HEMTs featured maximum oscillation frequencies in excess of $f_{MAX} = 300$ and 230 GHz on SiC and HR-Si, respectively. We report on both the small- and large-signal properties of the resulting transistors, including load-pull measurement data at W-band (94 GHz).

EXPERIMENTAL PROCEDURE

REGROWN n+ GAN OHMIC CONTACT BY AMMONIA MBE

Device fabrication began with mesa definition by Cl_2 based dry etching. Then, a SiO_2 mask was deposited by plasma enhanced chemical vapor deposition (PECVD), followed by the opening of the Ohmic contact windows by optical lithography and SF_6-based dry etching. The heterostructure was finally recessed in the contact region by Cl_2-based dry etching. Before loading the samples in the MBE chamber for n^+ GaN regrowth, the etched surface was cleaned in a solution 1:4 H_2O_2:H_2SO_4 solution and rinsed in water to ensure a smooth morphology. After regrowth, the SiO_2 mask was removed in diluted HF and the contacts were completed with the evaporation of Ti/Au metal pads. The total contact resistivity, measured from a TLM structure, is 0.25 Ω·mm which is made up from three contributions (M/S contact, n^+ GaN resistance, and 3D-2DEG contact resistance) as shown in Fig. 3.

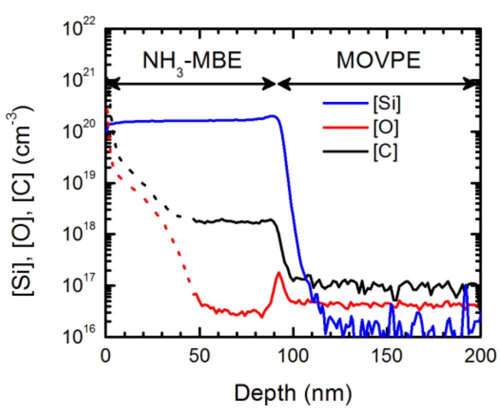

Figure 4. SIMS profile for Si, O and C impurities through the MBE regrown contact and the MOVPE original epitaxial HEMT layers.

SIMS analysis was performed in order to access the impurity profile for the regrown material, as shown in Fig. 4 for Si, C and O. It can be seen that the Si profile is flat in the doped region and the measured $[Si] = 1.7 \times 10^{20}$ cm^{-3} is consistent with the 1.8×10^{20} cm^{-3} carrier concentration measured by Hall effect on GaN doping calibration samples. The Si concentration decreases sharply at the regrowth interface and approaches the detection limit of $\sim 10^{16}$ cm^{-3} in the semi-insulating GaN layer. O and C concentrations in the highly doped region are $\sim 3 \times 10^{16}$ cm^{-3} and $\sim 2 \times 10^{18}$ cm^{-3}, respectively. More details on the regrowth process and materials characterization aspects can be found in a recently published article [5].

AlInN/GaN HEMTs with the improved Ohmic contacts based on the n+ GaN regrowth procedure described above were processed on semi-insulating SiC and HR-Si substrates in a manner similar to [6]. The devices were implemented with a 1 µm source-drain gap with a 50 nm footprint T-gate. The HEMTs are fully-passivated with a SiN encapsulation deposited by PECVD.

SMALL-SIGNAL DEVICE CHARACTERIZATION

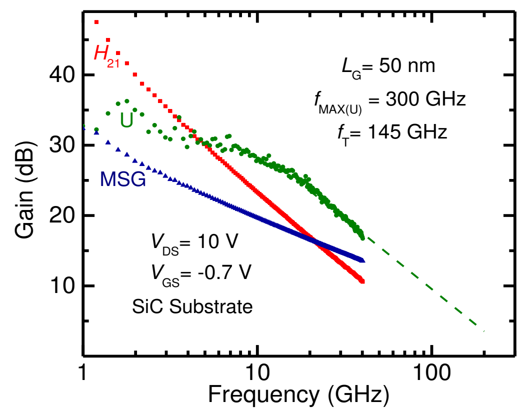

Figure 5. RF characteristics at the best maximum oscillation frequency for a 50 nm gate transistor fabricated on SiC.

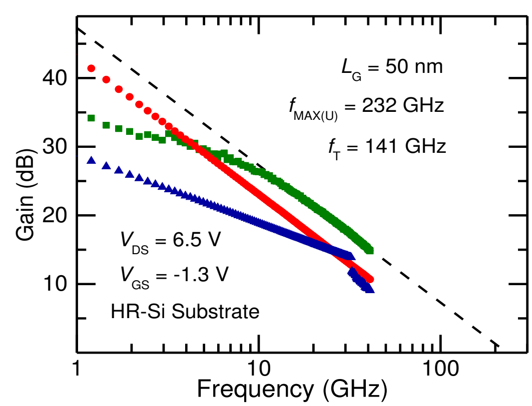

Figure 6. RF characteristics at the best maximum oscillation frequency for a 50 nm gate transistor fabricated on HR-Si.

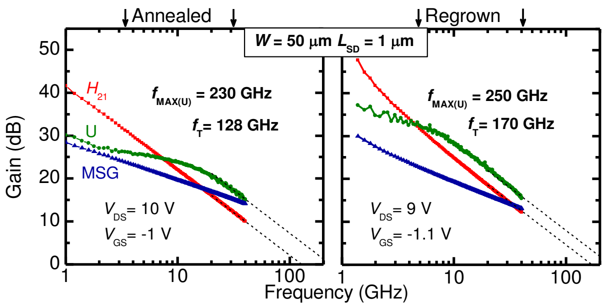

Figure 7. Performance comparison between nominally identical devices with traditional annealed contacts (left) and regrown contacts (right) for a 50 nm gate length.

Figs. 5-6 below show the results of small-signal measurements on both substrate types. Small-signal RF on-wafer measurements were performed from 0.2 to 40 GHz with an HP8510 vector network analyzer using an LRRM calibration with off-wafer impedance standards to remove pad effects in de-embedding. All other device parasitics are thus included in the data reported here.

It is noteworthy that similar $f_T \approx$ 140-145 GHz values are obtained for L_G = 50 nm on both substrates, while the f_{MAX} = 300 and 232 GHz on SiC and HR-Si, respectively. Interestingly, the peak f_{MAX} is reached at a lower applied drain voltage V_{DS} for devices built on HR-Si. The reason behind difference was not investigated but is likely related to differences in the thermal behavior of devices for SiC and HR-Si substrates.

It is interesting to compare the performance of a similar devices fabricated with annealed Ohmic and regrown contacts. Fig. 7 below shows the properties of annealed and regrown contact transistors built on SiC measured at similar bias points with V_{DS} = 9-10 V and $V_{GS} \approx -1$ V: regrown contacts enable a ~40 GHz increase in f_T in otherwise nominally identical devices, clearly demonstrating the benefits expected from previous studies on the impact of series resistances on the cutoff frequency in HEMTs [1-3].

LARGE-SIGNAL DEVICE CHARACTERIZATION

The large-signal performance of our transistors was characterized in a 94 GHz load-pull system developed at the ETH-Zurich. The system is described in detail in [7].

Figs. 8-9 show the results of load-pull characterization at W-band (94 GHz). The devices on SiC show a saturated output power of 1.51 W/mm and a peak power-added efficiency (PAE) of 8.5% at 1 W/mm for a gate length of 100 nm. Increasing the drain bias voltage to V_{DS} = 15 V resulted in a peak output power of 1.69 W/mm, however with a reduced peak PAE of 5% at 1.2 W/mm.

The devices on HR-Si shows a slightly lower 1.35 W/mm saturated output power but a higher peak PAE of 12% at 1 W/mm for a gate length of 50 nm at V_{DS} = 9 V. The fact that devices on HR-Si show a higher PAE than those on SiC is probably related to their different gate lengths. At this point it remains difficult to compare the power performance of nominally identical devices built on SiC and HR-Si. Beyond differences in thermal conductivity and internal junction temperatures, different current collapse properties tend to mask the true potential performance of each technology.

CONCLUSIONS

The increased processing complexity associated with n^+ GaN regrown contacts brings about important performance benefits to high Aluminum content barrier devices such as AlInN/GaN HEMTs. The developed process is stable, consistently yielding Ohmic contact resistances of 0.25 Ω·mm over several fabrication runs using multiple epitaxial layer stacks. The Ohmic contact regrowth approach has therefore proven most helpful in achieving repeatable low-contact resistance values on AlInN/GaN HEMTs, both on SiC and HR-Si substrates. W-band mm-wave circuits are now under development in the present HEMT technology and we hope to show early results at the conference.

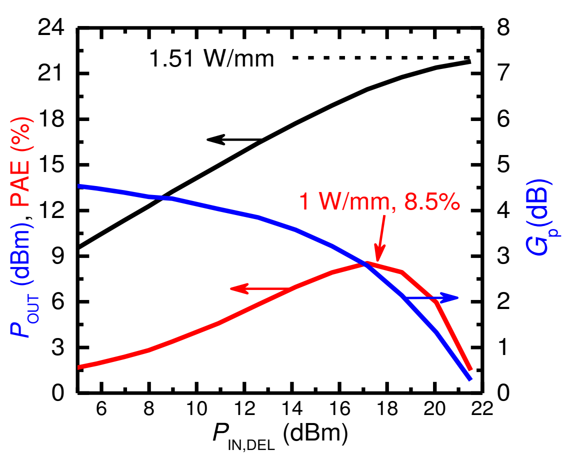

Figure 8. W-band (94 GHz) load-pull data for a 100 nm gate regrown contact AlInN/GaN HEMT on a SiC substrate. The device was biased at V_{DS} = 11 V and V_{GS} = –1.2 V.

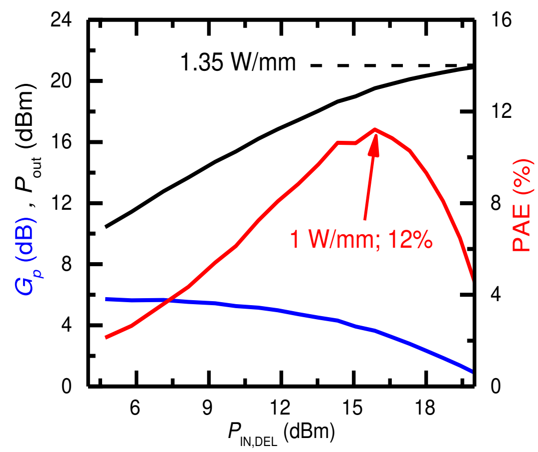

Figure 9. W-band (94 GHz) load-pull data for a 50 nm gate regrown contact AlInN/GaN HEMT on a HR-Si substrate. The device was biased at V_{DS} = 9 V and V_{GS} = –1.2 V.

Acknowledgements

The authors would like to thank the ETH-Zürich FIRST Laboratory staff for their support. This work was partly funded at EPFL and ETHZ by the Swiss National Science Foundation Project 200020_147142.

References

[1] P.J. Tasker and B. Hughes, "Importance of Source and Drain Resistance to the Maximum f_T of Millimeter-Wave MODFETs," IEEE Electron Dev. Lett., vol. 10, no. 7, pp. 291-293, July (1989).

[2] C.R. Bolognesi, A.C. Kwan, and D.W. DiSanto, "Transistor Delay Analysis and Effective Channel Velocity Extraction in AlGaN/GaN HFETs," Tech. Dig., 2002 IEEE IEDM, pp. 685 – 688 (2002).

[3] D.W. DiSanto and C.R. Bolognesi, "At-Bias Extraction of Access Parasitic Resistances in AlGaN/GaN HEMTs: Impact on Device Linearity and Channel Electron Velocity," IEEE Trans. on Electron Devices, vol. 53, no. 12, pp. 2914-2919 (2006).

[4] K. Shinohara, D. C. Regan, Y. Tang, et al., "Scaling of GaN HEMTs and Schottky Diodes for Submillimeter-Wave MMIC Applications," IEEE Trans. Electron Devices, vol. 60, no. 10. pp. 2982- 2989 (2013).

[5] L. Lugani, M. Malinverni, S. Tirelli, et al., "n+-GaN grown by ammonia molecular beam epitaxy: application to regrown contacts,"Appl. Phys. Lett., vol. 105, no. 20, pp. 202113 (2014).

[6] S. Tirelli, D. Marti, H. Sun, et al., "Fully Passivated AlInN/GaN HEMTs with f_T/f_{MAX} of 205/220 GHz," IEEE Electron Dev. Lett., vol. 32, no. 10, pp. 1364-1366 (2011).

[7] V. Teppati, H. Benedickter, D. Marti, et al., "A W-Band On-Wafer Active Load Pull System Based on Down-Conversion Techniques," Microwave Theory and Techniques IEEE Transactions on, Vol. 62, no. 1, pp.148-153 (2014).

Acronyms

f_{MAX}: Maximum oscillation frequency
f_T: Unity current gain cutoff frequency
EDX: Energy Dispersion X-ray analysis
HEMT: High Electron Mobility Transistor
HR-Si: High-Resistivity Silicon
MBE: Molecular Beam Epitaxy
MOVPE: Metalorganic Vapor Phase Epitaxy
PAE: Power-Added-Efficiency
PECVD: Plasma Enhanced Chemical Vapor Deposition
SEM: Scanning Electron Microscope
SIMS: Secondary Ion Mass Spectroscopy
2DEG: Two-Dimensional Electron Gas