# **Linköping University Post Print**

# Improved hot-wall MOCVD growth of highly uniform AlGaN/GaN/HEMT structures

Urban Forsberg, Anders Lundskog, A Kakanakova-Georgieva, Rafal Ciechonski and Erik Janzén

N.B.: When citing this work, cite the original article.

## Original Publication:

Urban Forsberg, Anders Lundskog, A Kakanakova-Georgieva, Rafal Ciechonski and Erik Janzén, Improved hot-wall MOCVD growth of highly uniform AlGaN/GaN/HEMT structures, 2009, JOURNAL OF CRYSTAL GROWTH, (311), 10, 3007-3010.

http://dx.doi.org/10.1016/j.jcrysgro.2009.01.045

Copyright: Elsevier Science B.V., Amsterdam.

http://www.elsevier.com/

Postprint available at: Linköping University Electronic Press http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-19663

1

Improved hot-wall MOCVD growth of highly uniform AlGaN/GaN/ HEMT structures

Urban Forsberg\*, A. Lundskog, A. Kakanakova-Georgieva, R. Ciechonski and E. Janzén

Department of Physics, Chemistry and Biology, Linköping University, SE-58 183 Linköping

\*urfor@ifm.liu.se

**Abstract** 

The inherent advantages of the hot-wall metal organic chemical vapor deposition (MOCVD

reactor (low temperature gradients, less bowing of the wafer during growth, efficient

precursor cracking) compared to a *cold-wall* reactor make it easier to obtain uniform growth.

However, arcing may occur in the growth chamber during growth, which deteriorates the

properties of the grown material. By inserting insulating pyrolytic BN (PBN) stripes in the

growth chamber we have completely eliminated this problem. Using this novel approach we

have grown highly uniform, advanced high electron mobility transistor (HEMT) structures on

4" SI SiC substrates with gas-foil rotation of the substrate. The nonuniformities of sheet

resistance and epilayer thickness are typically less than 3% over the wafer. The room

temperature hall mobility of the 2DEG is well above 2000 cm<sup>2</sup>/Vs and the sheet resistance

about 270  $\Omega$ /sqr.

PACS: 81.05.Ea; 81.15.Gh; 85.30.-z

Keywords: A3. Metalorganic chemical vapor deposition; B1. Nitrides; B3. High electron

mobility transistors

E-mail address: <a href="mailto:urfor@ifm.liu.se">urfor@ifm.liu.se</a> (Urban Forsberg)

#### 1. Introduction

The inherent advantages of the *hot-wall* MOCVD reactor (low temperature gradients, less bowing of the wafer during growth, efficient precursor cracking) compared to a *cold-wall* reactor make it easier to obtain uniform growth [1]. However, arcing may occur in the susceptor, which deteriorates the properties of the grown material. Here we will present a solution to this problem. Using this novel approach we have grown highly uniform, advanced HEMT structures on 3" and 4" semi-insulating (SI) SiC substrates with gas-foil rotation of the substrate. AlGaN/GaN based high electron mobility transistors (HEMT) have received an increased attention in last years due to their attractive properties [2-4] which are suitable for high power, high temperature and high frequency applications.

# 2. Arcing

A hot-wall susceptor consists of several building blocks including roof, bottom, sidewalls and rotation cassette mounted together. The building blocks are made of high-purity graphite and are coated with TaC to prevent impurities from being incorporated into the grown epilayers. The susceptor is heated by current induced by a surrounding RF coil. When the current passes from one susceptor part to another, arcing may occur. The mm<sup>2</sup>-sized arcs (hot spots) are not stable in time and the current density is extremely high causing a large temperature increase locally.

#### Arcing will:

- Cause decomposition of the TaC coating material exposing the underlying graphite
- Cause release of impurities from the graphite which may be incorporated into the grown epilayer
- Cause release of larger graphite particles visible by eye, resulting in particle downfalls on the substrate

- Cause localized changes in temperature distribution resulting in temperature fluctuation of the entire susceptor and fluctuation of the RF power input. This will influence the deposition profile.
- Cause disturbance in the rotation of the satellite carrier, resulting in reduced or lack of substrate rotation. This disturbance is most likely due to secondary RF induction in the satellite carrier
- Drastically reduce the life time of susceptor parts and thereby increase the running cost
- Drastically reduce the run-to-run reproducibility

The contact resistivity between two adjacent susceptor parts varies along the contact area. This could be due to e.g. TaC surface roughness or graphite particles at the interface. The RF induced current will choose the path of least resistance between the two different susceptor parts. If the contact resistivity locally is increased but the gap between the susceptor parts still is small, the induced electric field at the gap will be large and arcing may occur. Once an arc is created it destroys the coating and the graphite material in the surrounding of the arc, see fig 1. When the coating and the graphite material are gone, the arc disappears or moves to another part of the interface; this is seen as the large black graphite area in fig. 1.

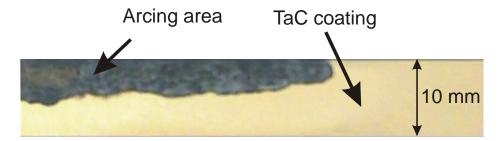


Fig 1. Part of the sidewall where arcing has destroyed the TaC coating. The black area extends over several centimeters.

One obvious solution to the arcing problem is to eliminate the circular current loop, see fig 2., that passes through all 4 susceptor parts (roof, sidewall, bottom, sidewall and back to the roof). This can be done by inserting pyrolytic BN (PBN) stripes, with resistivity of about  $1\cdot10^{10} \Omega cm$  at  $1000 \, ^{\circ}C$ , between the susceptor parts, see fig 2. When the arcs were eliminated the fluctuations of the RF power input needed to regulate the temperature disappeared, see Fig 3. The lifetime of the susceptor is also very long, exceeding several hundred hours, when no arcs are present. The growth is stable and the run-to-run variations are similar to variations over a wafer for properties like sheet resistance, etc

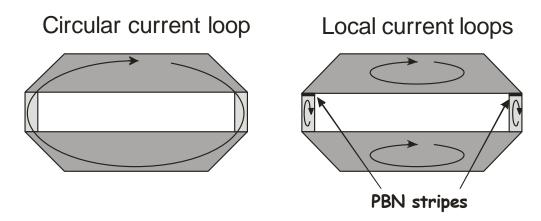


Fig 2. Circular current loop in a standard hot-wall susceptor. The PBN stripes effectively eliminate the arcing and break the circular current loop into local current loops.

#### 3. Epitaxial growth and characterization of 3" and 4" HEMT structures

The HEMT structures were grown on SI 4H-SiC substrates in an improved hot-wall MOCVD reactor equipped with PBN stripes to avoid arcing. The structures were grown at a total reactor pressure of 50 mbar in a mixture of H<sub>2</sub> and N<sub>2</sub> carrier gases. The wafer was rotating during growth. Ammonia, NH<sub>3</sub>, as a precursor for N, and trimethylaluminum (TMAl) and trimethylgallium (TMGa) as precursors for Al and Ga, respectively, were delivered at V/III ratios in the range of 1045 (AlN growth, NH<sub>3</sub> flow rate of 2 slm) and 385 (GaN growth, NH<sub>3</sub>

flow rate of 4 slm). The susceptor temperature was 1100 °C (AlN growth) and 1000 °C (GaN and  $Al_xGa_{1-x}N$  growth).

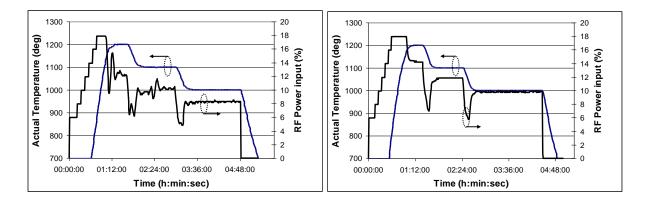


Fig. 3. The left figure shows the temperature reading and the RF power input using the original design of the hot-wall MOCVD reactors and the right figure shows the same readings using the improved design with PBN stripes.

The thickness of the GaN layer is of the order of micrometers and is conveniently measured (and mapped over the whole wafer) using an interference technique [1]. Mercury probe capacitance – voltage (CV) measurements were used to extract information on the 2DEG sheet carrier density,  $n_s$  ( $n_s = \frac{1}{qA} \int C dV$ , where q, A, C, and V are the elementary charge, contact area, capacitance and bias voltage, respectively), and the pinch-off voltage,  $V_p$ , as well as the thickness, t, of the  $Al_xGa_{1-x}N$  barrier. In addition we could determine that the GaN buffer layer was semi-insulating with a net doping concentration at least less than  $1x10^{14}$  cm<sup>-3</sup>. The measurements were done at 10 kHz with a 1 mm diameter mercury contact. An  $\epsilon$  value of 8.9 was used.

The sheet resistance,  $R_{\square}$ , was measured using a non-contact eddy current technique. The measurement point was 3 mm in diameter.

For Hall measurement experiment, the sample was cut into a square of 5x5 mm. 1500 Å thick Al ohmic contacts forming lamella-type van der Pauw pattern were deposited at the corners of the sample. In Hall measurements, a magnetic field of 0.75 T in magnitude, perpendicular to the sample, was used and the current was set to 1 mA. Hall measurements were performed in the temperature range from 80 to 600 K.

#### 4. Results and discussion

Al<sub>0.22</sub>Ga<sub>0.78</sub>N/AlN/GaN/AlN HEMT structure grown on a 4" SI 4H SiC wafer

The structure starts with a thin AlN nucleation layer followed by a 1.8  $\mu m$  undoped, SI GaN layer, a 2nm AlN exclusion layer and a 23 nm Al $_x$ Ga $_{1-x}$ N barrier. The role of the exclusion layer is to decrease the random-alloy scattering experienced by the 2DEG due to penetration into the barrier [5]. The epi thickness (1.77  $\mu m \pm 2.8$  %) and the sheet resistance (268  $\Omega$ /sqr  $\pm$  2.1 %) are highly uniform, see Fig 4. The results from mercury probe CV-measurements are: Sheet carrier density 9.9E12 cm $^{-2}$ , V(pinch-off) = -5.3 V, thickness of (AlGaN + AlN) = 25 nm, no electrons in the GaN layer. The results from Hall measurements are shown in Fig 5. At temperatures above 200 K the scattering of optical phonons is limiting the mobility and our results are close to the theoretical limits with a hall mobility of 2310 cm $^2$ /Vs at room temperature. The hall mobility is as high as 800 cm $^2$ /Vs at 450K, a relevant high-power-device operating temperature. A similar structure but without the AlN exclusion layer shows a mobility of 1560 cm $^2$ /Vs at room temperature and the lower mobility is due the random ally scattering at the AlGaN/GaN interface. It is apparent that the exclusion layer is effective in increasing the mobility also at temperatures when the optical-phonon scattering should limit the mobility.

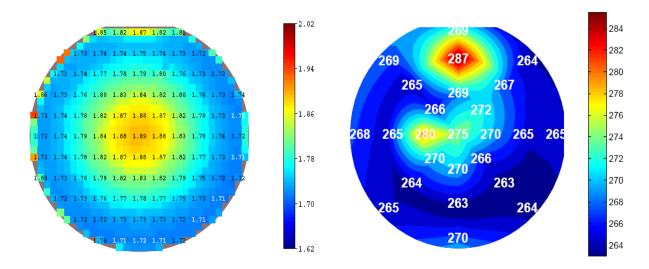
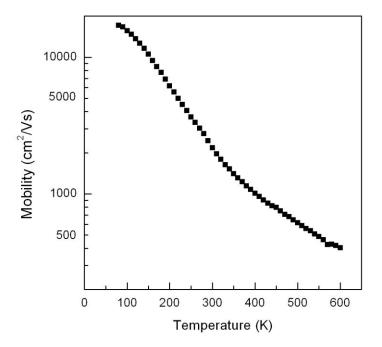


Fig. 4 (left)A map (in  $\mu$ m) of the total epi thickness of an AlGaN/AlN/GaN HEMT structure grown on a 100 mm SI 4H-SiC substrate. The thickness is 1.77  $\mu$ m  $\pm$  2.8 %. (right) A map (in  $\Omega$ /sqr) of the sheet resistance of the same epiwafer. The sheet resistance is 268  $\Omega$ /sqr  $\pm$  2.1 %.



 $Al_{0.25}Ga_{0.75}$  Fig 5. 2DEG Hall mobility as a function of temperature for a sample from the epiwafer shown in Fig. 4.

N/AlN/GaN/Al<sub>0.07</sub>Ga<sub>0.93</sub>N/AlN HEMT DH-structure grown on a 3" SI 4H SiC wafer

Here the SI, undoped, 2.0 μm thick Al<sub>0.07</sub>Ga<sub>0.93</sub>N buffer layer is followed by a strained 50 nm

GaN layer. The 2DEG is developed at the AlN/GaN interface. The room-temperature Hall

2DEG mobility is 1720 cm<sup>2</sup>/Vs. The uniform properties of the DH HEMT structure are shown in Fig.6.

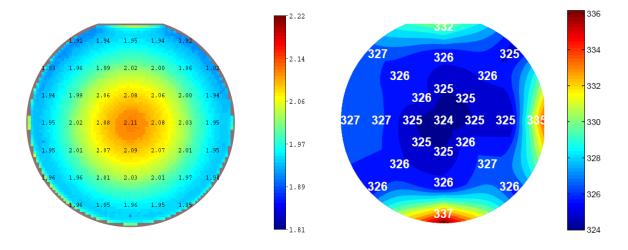


Fig. 6 The uniformity of the thickness (left, 1.99  $\mu m \pm 2.6$  %) and the sheet resistance (right, 327  $\Omega$ /sqr  $\pm$  1.1 %) for a DH HEMT structure grown on a 3" SI SiC substrate.

# 5. Conclusion

We have shown that it is possible to completely eliminate the detrimental arcing in hot-wall MOCVD reactors by inserting insulating PBN stripes between the susceptor parts. In such improved hot-wall reactor it is possible to grow AlGaN/AlN/GaN HEMT structures with state-of-the-art properties very uniformly on large area (4") SI SiC substrates. Nonuniformities of epilayer thickness and sheet resistance as well as run-to-run variations of less than 3% (sigma/mean) can easily be achieved on 4" substrates. We have also demonstrated that it is possible to achieve 2DEG hall mobilities at room temperature close to the theoretical limit using device-relevant sheet carrier densities.

# Acknowledgements

Support from Knut and Alice Wallenberg's Foundation (KAW), Key Organisation for Research in Integrated Circuits in GaN Technology (KORRIGAN), Swedish Research Council (VR), Swedish Foundation for Strategic Research (SSF) and Epigress AB/Aixtron AG is gratefully acknowledged.

## References

- [1] A. Kakanakova-Georgieva, U. Forsberg, I.G. Ivanov and E. Janzén, J. Crystal Growth 300 (2007) 100-103
- [2] N. Maeda, T. Saitoh, K. Tsubaki, T. Nishida, and N. Kobayashi, Jpn. J. Appl. Phys., part 2 38, L987 (1999).
- [3] M. A. Khan, X. Hu, A. Tarakji, G. Simin, J. Yang, R. Gaska, and M. S. Shur, Appl. Phys. Lett. 77, 1339 (2000).
- [4] Y.-F. Wu, J. P. Ibbetson, P. Parikh, B. P. Keller, U. K. Mishra, and D. Kapolnek, IEEE Trans. Electron Devices **48**, 586 (2001).
- [5] R.S. Balmer, K.P. Hilton, K. Nash, M.J. Uren, D.J. Wallis and T. Martin, Semicond. Sci. Technol. 19, L65 (2004)

#### Figure captions

Fig 1. Part of the sidewall where arcing has destroyed the TaC coating. The black area extends over several centimeters.

Fig 2. Circular current loop in a standard hot-wall susceptor. The PBN stripes effectively eliminate the arcing and break the circular current loop into local current loops.

Fig. 3. The left figure shows the temperature reading and the RF power input using the original design of the hot-wall MOCVD reactors and the right figure shows the same readings using the improved design with PBN stripes.

Fig. 4. (left)A map (in  $\mu$ m) of the total epi thickness of an AlGaN/AlN/GaN HEMT structure grown on a 100 mm SI 4H-SiC substrate. The thickness is 1.77  $\mu$ m  $\pm$  2.8 %. (right) A map (in  $\Omega$ /sqr) of the sheet resistance of the same epiwafer. The sheet resistance is 268  $\Omega$ /sqr  $\pm$  2.1 %.

Fig 5. 2DEG Hall mobility as a function of temperature for a sample from the epiwafer shown in Fig. 4.

Fig. 6. The uniformity of the thickness (left, 1.99  $\mu m \pm 2.6$  %) and the sheet resistance (right,  $327 \Omega/\text{sqr} \pm 1.1$  %) for a DH HEMT structure grown on a 3" SI SiC substrate.