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► **To cite this version:**

Kathia Harrouche, François Grandpierron, Lyes Ben-Hammou, Etienne Okada, F Medjdoub. Pushing Q-band power performances by means of buffer engineering in AlN-GaN HEMTs. 46th Workshop on Compound Semiconductor Devices and Integrated Circuits (WOCSDICE 2023), May 2023, Palerme (Italie), Italy. hal-04438176

**HAL Id: hal-04438176**

**<https://hal.science/hal-04438176v1>**

Submitted on 5 Feb 2024

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# Pushing Q-band power performances by means of buffer engineering in AlN-GaN HEMTs

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## Abstract

We report on AlN/GaN HEMT technology for millimetre-wave applications with various buffer architectures. A high carbon-doped buffer enables high electron confinement at the expense of trapping effects, which is attributed to the enhanced point defects and dangling bonds when using higher carbon concentration. On the other hand, reduced carbon-doped buffer combined with the insertion of an AlGaIn back barrier underneath a non-intentionally doped GaN channel layer enables not only low trapping effects but also prevents punch through effects and related drain leakage current under high drain bias. This results in a unique combination of excellent electron confinement and low trapping effect while using gate lengths as low as 100 nm and high drain bias ( $\geq 20$  V). As a result, the optimized structure using a thin AlGaIn back barrier enabled outstanding RF performances at 40 GHz with a record PAE of 70% and 66% under high output power density at  $V_{DS} = 20$  V in pulsed and CW mode, respectively.

## Introduction

The last decade has seen a remarkable progress with GaN HEMTs for use in high frequency power amplification owing to its outstanding material properties. Recent improvements have allowed the demonstration of the next generation millimetre-wave applications such as SATCOM, military and 5G networks. In this context, high power added efficiency (PAE) at high frequency together with an excellent robustness are mandatory. This turned to be the main challenge for compact solid-state power amplifiers. Short GaN HEMTs on SiC substrate have already demonstrated high efficiencies in Ka band. Nevertheless, at higher frequency, the efficiency and robustness under high electric field ( $V_{DS} \geq 20$  V) are still limited due to trapping effects and poor electron confinement when downscaling the device size. In this work, we performed a comparison between high and medium carbon-doped buffer structures with the aim of pushing the PAE limits of GaN HEMTs while maintaining low trapping effects.

## Experimental

The heterostructures have been grown by metal organic vapour deposition (MOCVD) on 4-inch substrates. They consist in 150 nm undoped GaN channel layer, a 3 nm AlN barrier layer, and a 6 nm  $Si_3N_4$  cap layer. Two different buffer layers have been used in order to study the impact on both trapping effects and electron confinement. The first structure consists of a high carbon concentration GaN buffer of  $2 \times 10^{19}$  cm<sup>-2</sup> while the second structure includes a reduced carbon concentration buffer of  $5 \times 10^{18}$  cm<sup>-2</sup> combined with a 100 nm AlGaIn back barrier (BB) with 25% Al-content. More process details can be found in [1].

## Results and Discussion

Fig.1 shows transfer characteristics of the structure with high C-doping using a compliance fixed at 150 mA/mm and swept from  $V_{DS} = 2$  V to 20 V in order to evaluate the 2DEG electron confinement.  $2 \times 50$   $\mu$ m transistors with a gate length ( $L_G$ ) of 100

nm and a gate-to-drain distance ( $L_{GD}$ ) of 0.5  $\mu$ m show a good electron confinement reflected by a DIBL as low as 60 mV/V. However, the transistors display rather high trapping effects due to the point defects and nitrogen vacancies when using high carbon concentration as shown in Fig.2 [2]. Load-pull measurements at 40 GHz have been performed on the same device. Fig.5 shows CW and pulsed performances at  $V_{DS} = 20$  V. A peak PAE of 60% associated with a  $P_{OUT}$  of 3.2 W/mm has been achieved in CW mode. In pulsed mode, these devices deliver an outstanding combination PAE/ $P_{OUT}$  of 70%/3.5 W/mm at  $V_{DS} = 20$  V.

Fig.3 shows the transfer characteristics of the structure with medium C-doping + thin AlGaIn BB. An excellent electron confinement is observed with a much lower DIBL of less than 30 mV/V for a 100 nm gate length while maintaining low drain leakage current and high robustness up to  $V_{DS} = 20$  V owing to the high polarization of the AlGaIn BB enhancing the electron confinement. Moreover, this structure showed low trapping effects (Fig. 4) owing to the moderate carbon concentration of  $5 \times 10^{18}$  cm<sup>-2</sup> located 250 nm away from the 2DEG [3]. CW and pulsed Load-Pull measurements at 40 GHz demonstrates state-of-the-art PAE in CW (pulsed) of 67% (70%) associated with a  $P_{OUT}$  of 3.5 W/mm (4.2 W/mm) at  $V_{DS} = 20$  V. A summary of the power performance as a function of  $V_{DS}$  for both structures appears in Fig.7. These device designs enable high performances under high voltage operation despite the use of short gate length as low as 100 nm. Moreover, the comparison between the two structures reveals enhanced performances for the structure with medium C-doping and AlGaIn BB. This translates the reduced trapping effects and enhanced electron confinement under high drain bias at 40 GHz owing to the low carbon concentration and the high polarization of the AlGaIn BB.

## Conclusions

In this work, we performed a comparison between two HEMT structures with high and medium carbon concentration with the insertion of a thin AlGaIn BB. The 100 nm transistors with high carbon concentration show a good electron confinement under high electric field at the expense of trapping effects. This limits the CW large signal performances as compared to the pulsed ones. On the other hand, the structure with medium C-doping and additional thin AlGaIn BB shows an excellent electron confinement with significantly reduced low trapping effects. As a result, 40 GHz large signal performances revealed unprecedented CW power performances.

## Acknowledgments

The authors would like to acknowledge the company SOITEC Belgium for high-quality material delivery and the support of the French RENATECH network, DGA/CNRS funded GREAT project and LABEX GANEXT ANR-11-LABX-0014.

## References

- [1] K. Harrouche, et al., *Appl. Phys. Express* 15 116504, (2022).
- [2] K. Harrouche, et al., *Micromachines*. 14(2), 291 (2023).

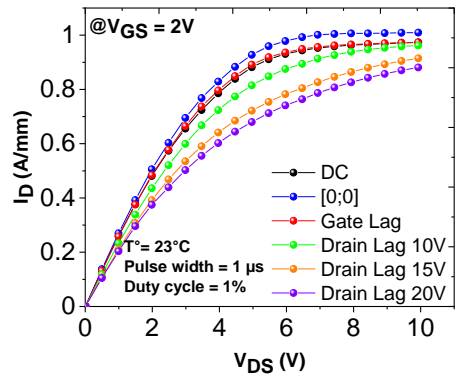
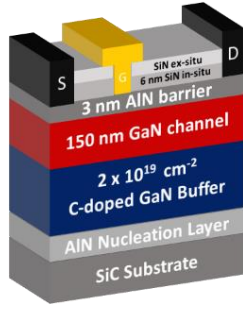
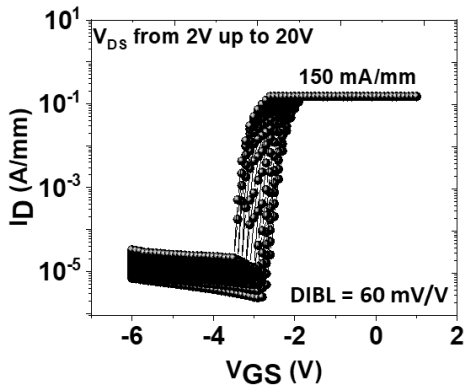


Fig. 1. Transfer characteristics of  $2 \times 50 \mu\text{m}$  AlN/GaN HEMT for  $L_{\text{GD}} = 0.5 \mu\text{m}$  and  $L_{\text{G}} = 100 \text{ nm}$  of the structure with high C-doping buffer

Fig. 2. Open channel  $I_{\text{D}}-V_{\text{DS}}$  output characteristics of  $2 \times 50 \mu\text{m}$  AlN/GaN HEMT for  $L_{\text{GD}} = 0.5 \mu\text{m}$  and  $L_{\text{G}} = 100 \text{ nm}$  of the structure with high C-doping buffer

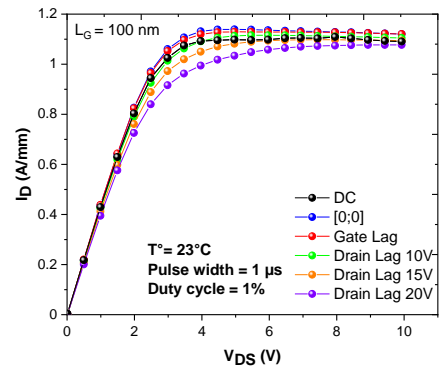
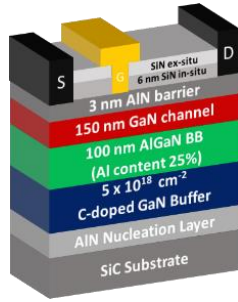
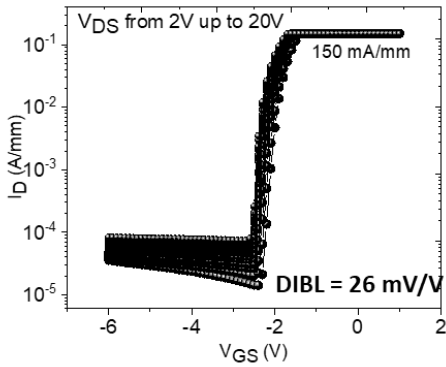


Fig. 3. Transfer characteristics of  $2 \times 50 \mu\text{m}$  AlN/GaN HEMT for  $L_{\text{GD}} = 0.5 \mu\text{m}$  and  $L_{\text{G}} = 100 \text{ nm}$  of the structure with medium C-doping buffer + thin AlGaIn BB

Fig. 4. Open channel  $I_{\text{D}}-V_{\text{DS}}$  output characteristics of  $2 \times 50 \mu\text{m}$  AlN/GaN HEMT for  $L_{\text{GD}} = 0.5 \mu\text{m}$  and  $L_{\text{G}} = 100 \text{ nm}$  of the structure with medium C-doping buffer + thin AlGaIn BB

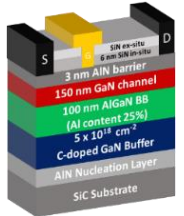
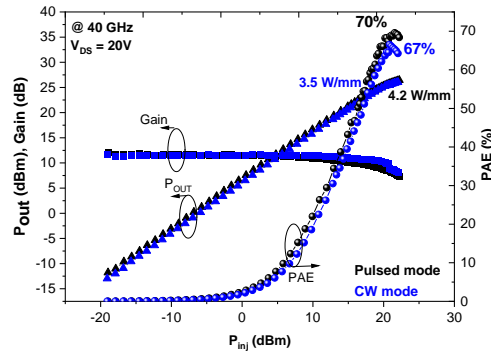
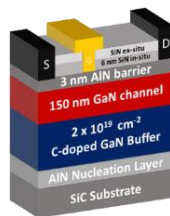
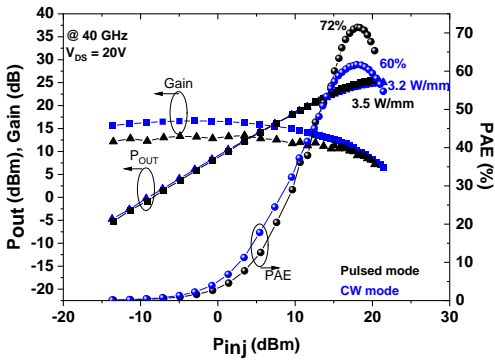


Fig. 5. Typical CW and pulsed large signal performances of  $2 \times 50 \mu\text{m}$  AlN/GaN HEMT for  $L_{\text{GD}} = 0.5 \mu\text{m}$  and  $L_{\text{G}} = 100 \text{ nm}$  of the structure with high C-doping buffer

Fig. 6. Typical CW and pulsed large signal performances of  $2 \times 50 \mu\text{m}$  AlN/GaN HEMT for  $L_{\text{GD}} = 0.5 \mu\text{m}$  and  $L_{\text{G}} = 100 \text{ nm}$  of the structure with medium C-doping buffer + thin AlGaIn BB

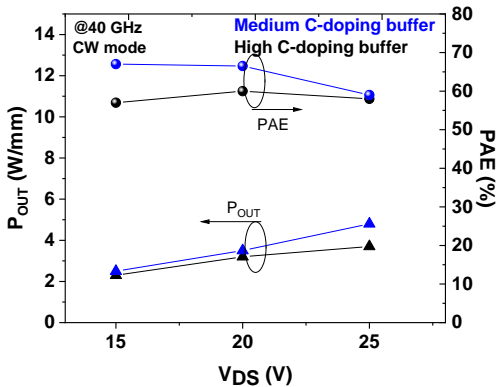


Fig. 7. CW  $P_{\text{OUT}}$  and PAE as a function of  $V_{\text{DS}}$  from AlN/GaN HEMTs with high C-doping buffer versus medium C-doping + thin AlGaIn BB