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C-doped AlN/GaN HEMTs for High efficiency mmW applications

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***Abstract* — We report on high power-added-efficiency using AlN/GaN heterostructure with a carbon doped buffer layer for millimeter wave applications (C-doped HEMTs). The carbon doped HEMTs show high electrical characteristics with a maximum drain current density I_d of 1.5 A/mm, an extrinsic transconductance G_m of 500 mS/mm and a maximum oscillation frequency f_{max} above 200 GHz while using a gate length of 120 nm. The high RF performance obtained on the carbon doped HEMT combined to an excellent electron confinement under high bias enabled to achieve a state-of-the-art combination at 40 GHz of output power density (P_{OUT} = 7 W/mm) and power added efficiency (PAE) above 50% up to V_{DS} = 25V in pulsed mode.**

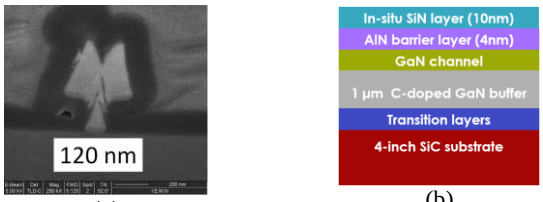
Keywords— **high electron mobility transistors (HEMTs), GaN, Carbon doped, output power density and power added efficiency (PAE).**

I. Introduction

Owing to its outstanding properties, GaN based High electron Mobility Transistors (HEMTs) are a promising candidate for high frequency high power applications. Especially considering the increasing need in terms of bandwidth wireless communication such as 5G or SATCOM. One of the key challenge for the GaN technology is to achieve high power-added-efficiency and output-power-density combination in the millimeter-wave range. That is why, the traveling wave tube amplifiers (TWTA) are still widely used in this frame. Even though attractive efficiencies with GaN devices (well-beyond 40%) have been already demonstrated up to Ka band [1][2][3][4][5], rather limited PAE has been reported so far in the Q band (40 GHz) and above. For high frequency applications requiring short gate lengths, different configurations of buffer layers have been employed. One potential solution is the C-doped buffer that has been widely adopted in high voltage power switching applications[6]. It has the advantage compared to Fe-doped GaN buffers of lower memory effects[7], lower risk of diffusion and the elimination of contamination risks when used in Si CMOS-based foundries. In this paper, we demonstrate the potential of the C-doped HEMTs for achieving high output power density combined to high power-added-efficiency at 40 GHz.

II. Material and Device Processing

The AlN/GaN heterostructures were grown by metal organic chemical vapor deposition (MOCVD) on 4 in. SiC substrates. The HEMT structure consists of transition layers to GaN, a 1 µm-thick C-doped GaN buffer layer followed by an undoped GaN channel, a 4.0 nm ultrathin AlN barrier layer and a 10-nm-thick in situ Si_3N_4 cap layer. The in situ SiN cap layer is used both as early passivation and to prevent strain relaxation [8][9][10]. Room-temperature Hall measurements showed high electron sheet concentrations of 1.8×10^{13} with an electron mobility about 1100 $cm^2V^{-1}s^{-1}$.



(a) (b)

Fig.21. : a) FIB view of the 0.12 µm T-gate and schematic cross section of C-doped HEMT.

A Ti/Al/Ni/Au metal stack followed by a rapid thermal annealed has been used to form the ohmic contacts directly on top of the AlN barrier layer by etching the in situ Si_3N_4 layer. Device isolation was achieved by nitrogen implantation. Ohmic contact resistance (R_c) extracted from linear transmission line model (TLM) structures was as low as 0.3 Ω.mm for both heterostructures. Then, a 0.12 µm Ni/Au T-gate length was defined by e-beam lithography (see Fig. 2.1). The SiN underneath the gate was fully removed by SF_6 plasma etching. The gate-source and gate-drain spacings were 0.3 and 2 µm, respectively, and the device width was 50 µm. Finally, 200 nm PECVD Si_3N_4 was deposited as final passivation.

III. DC and Small Signal Characterization

DC measurements have been carried out using a Keysight A2902A static modular and source monitor. Fig. 3.1 shows the typical I-V characteristics of the structure. The gate source voltage was swept from -6V to +2V with a step of 0.5 V. A maximum current drain density (I_{Dmax}) of 1.5

A/mm is observed at V_{DS} = 10V and V_{GS}=2V reflecting the high carrier concentration.

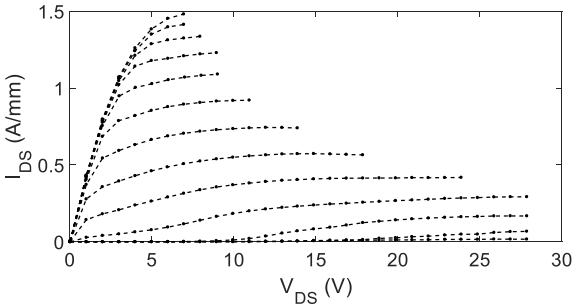


Fig. 3.2 Output characteristics of C-doped HEMT.

From, the transfer characteristics, shown in Fig. 3.2 at V_{DS} = 6, 8 and 10 V, an excellent device pinch-off behavior is observed with a low off-state leakage current below 10 µA/mm. Moreover despite the use of short gate lengths, a good electron confinement is obtained. Furthermore, a high extrinsic transconductance G_m around 500 mS/mm at V_{DS}=10V is achieved. At these respective biases, using Rhode and Schwarz ZVA67GHz, the cut-off frequency (f_T) and maximum frequency oscillation f_{max} are extracted from the scattering (S) parameters. Good RF performances are achieved with f_T = 60 GHz and f_{max} = 242 GHz. It can be noticed that a high f_{max} / f_T ratio above 4 is observed, which can be explained by the favorable aspect ratio between the gate length and the gate to channel distance (ultrathin 4nm barrier), the high carrier concentration and the low parasitic gate capacitance.

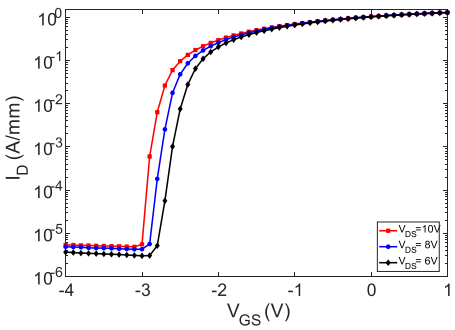


Fig 3.2. : Transfer characteristics at VDS = 6, 8, 10 V of C-doped HEMT.

IV. LARGE SIGNAL CHARACTERIZATION AT 40 GHZ

Large signal characterizations at 40 GHz have been carried out on in pulsed mode (1 µs width and 1% duty cycle) under deep AB class conditions. Fig 4.1 shows the pulsed power performance of a 0.12×50 µm² AlN/GaN HEMT at 40 GHz with V_{DS} = 15V, 20V, and 25 V. A saturated P_{OUT} (output power density) of 7 W/mm was achieved with a peak PAE of 52% associated to a linear power gain above 8 dB. Moreover, at V_{DS} = 10 V a peak PAE as high as 56% combined with an output power density of 1.6 W/mm has been reached.

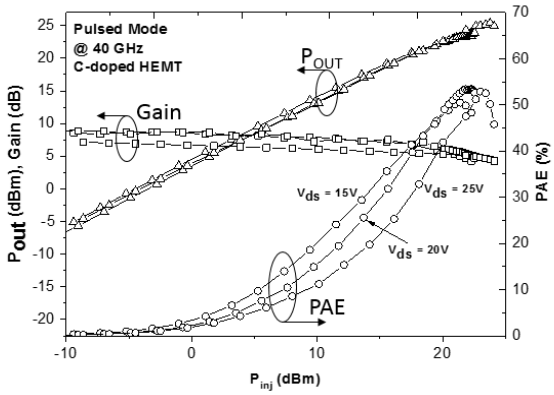


Fig.4.1. : Pulsed power performance of a 0.12×50 µm² HEMT at 40 GHz with V_{DS} = 15, 20, 25V.

The output power density evolves linearly as a function of the drain bias (see Fig 4.2) with no sign of saturation even at V_{DS} = 25V reflecting the high material quality and associated processing. It is worth noting that the C-doped structure shows the ability to deliver a PAE above 50% up to V_{DS} = 25V.

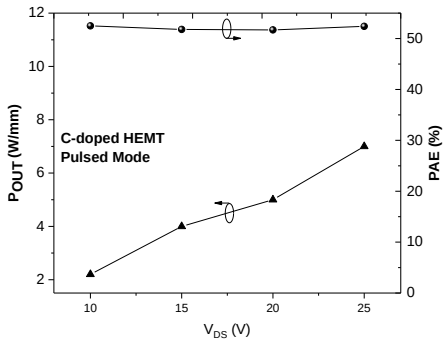


Fig.4.2. : Pulsed output power density (triangle) and PAE (circle) as function of V_{DS} at 40 GHz.

As can be seen from the benchmark in Fig. 4.3, the achieved PAE / P_{OUT} combination at 40 GHz compares favorably to the state-of-the-art.

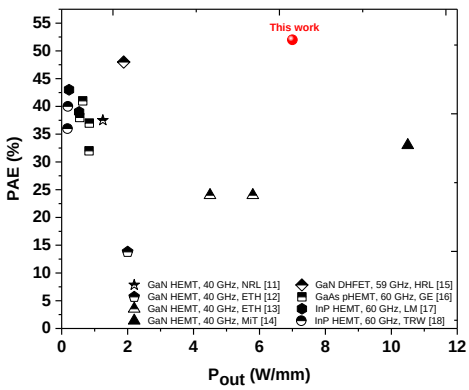


Fig.4.2. : Benchmark of the output RF power density vs PAE for Q and V band [11] [12] [13] [14] [15] [16] [17] [18].

V. CONCLUSION

This work shows that a careful architecture of Carbon doped buffer layers can be employed in order to perform high performance millimeter-wave GaN devices. The C-doped structure delivers high performances illustrated by a state-of-the-art combination of PAE (> 50%) and an output power density of 7 W/mm at 40 GHz and V_{DS} = 25V.

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