RF Noise and Power Performances of AlGaN/GaN on Si(111) Substrates

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Abstract - **High performances was achieved on AlGaN/GaN HEMTs based on Si(111). Devices with 0.17-µm and 0.3-µm gate lengths are fabricated on two different layer growth at TIGER laboratory. RF noise and power performances are carried out on these transistors. The 0.17 × 100 µm² devices exhibit a unity current gain cutoff frequency (f_t) of 46 GHz, and a maximum frequency (f_{max}) of 92 GHz at V_{DS} = 10 V. Also, a minimum noise figure (NF_{min}) of 1.1 dB and an available associated gain (G_{ass}) of 12 dB are obtained at V_{DS} = 10 V and f = 10 GHz. The 0.3 × 300 µm² devices demonstrate a drain-to-source current density Ids = 925 mA/mm at V_{GS} = 0 V and a maximum extrinsic transconductance (G_m) of 250 mS/mm. Furthermore, a high output power density of 1.9 W/mm associated to a PAE of 18% and a linear gain of 16 dB are measured at f = 10 GHz and V_{DS} = 30 V. These performances are the best ever reported for AlGaN/GaN HEMTs based on silicon substrates at this frequency.**

I. Introduction

It was shown that AlGaN/GaN High-Electron Mobility Transistors (HEMTs) constitute, at present, an excellent candidate for telecommunication broadcasting in the emission and reception chains. If higher power capabilities are demonstrated since several years, more recently, it was shown that the RF noise properties are very close to those of GaAs based devices. Consequently, AlGaN/GaN HEMTs may be now used for high power amplifier (HPA) and low noise amplifier (LNA) making. In the last case, the material properties make it possible to simplify the circuit avoiding the limiter protection circuitry to present damage to the high sensitivity receive chain.

In this frame, AlGaN/GaN HEMTs grown on silicon substrate constitute an interesting alternative for the making of low cost modules.

In this paper, AlGaN/GaN HEMTs on silicon substrate are developed in order to obtain high power operations and good RF noise performance at high frequencies. The III-Nitride wide bandgap material attracts much attention because of its superior physical properties such as high breakdown electric field, high electron saturation velocity and excellent thermal conductivity. Significant progress was made in recent years in material growth and process technology. These improvements are promising for power devices at S-band, X-band and K-band [1][2][3] and low noise amplifiers (LNA). The increase of applications such as satellite constellations as well as passive imaging systems needs the realization of high performance low noise amplifiers [4][5]. AlGaN/GaN on silicon substrates with its large area availability and its low cost is an excellent candidate for the making of robust LNAs.

In this study, the growth layer and the process device are first presented. Afterwards, the microwave performance is described in term of RF noise and power amplification.

II. Device Structure and Fabrication

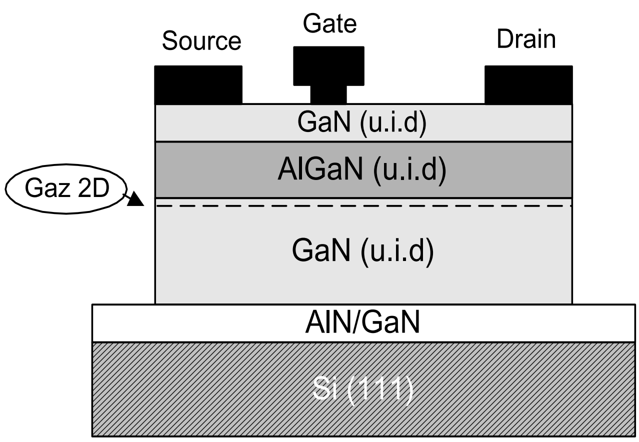

Fig. 1. Device cross section

In our experiment, two similar epitaxial layers are used. Both layers are obtained by Molecular Beam Epitaxy (MBE) grown on Si(111).Device cross section is shown in Fig. 1. The first epitaxial layer (sample1) stems from CRHEA laboratory and it consists of 50 nm of AlN nucleation layer, 0.5 µm of GaN/AlN sequence, 1.5 µm of GaN buffer, 30 nm of $Al_{0.26}Ga_{0.74}N$ barrier and 1 nm of GaN cap layer. Layers are undoped. The second epitaxial layer (sample2) is made by Picogiga International Company. The epilayer contains 40 nm of AlN nucleation layer, 250 nm of GaN layer, 250 nm of AlN layer, 2.5 µm of unintentionally doped GaN buffer, 25 nm of $Al_{0.31}Ga_{0.69}N$ barrier and 1 nm of unintentionally doped GaN cap layer. Both layers present high resistivity substrates.

Device isolation is achieved by Reactive Ion Etching (RIE) using a $SiCl_4$ gas. Ohmic contacts are formed using a Rapid Thermal Annealing (RTA) of evaporated Ti/Al/Ni/Au (12/200/40/100 nm) metallization at 900°C during 30s under nitrogen atmosphere. The gate to source (L_{gs}) and the source to drain (L_{gd}) device spacing are respectively 1 µm and 1.5 µm. T-gates are made by using a bilayer PMMA/MMA-MAA resist scheme and a Pt/Ti/Pt/Au (25/25/25/300 nm) metallization.

III. Results and Discussion

The DC characteristics measured on both samples using a HP4142B modular source and monitor, show good static drain currents. Sample1 device (0.17 × 100 µm²) gives a maximum drain current I_{DS} = 550 mA/mm at V_{GS} = 1 V and V_{DS} = 10 V. Pinch-off voltage is close to -6 V. At 10 GHz, the intrinsic transconductance (g_m) shows a peak value of 215 mS/mm at V_{GS} = -3.5 V and V_{DS} = 10 V.

Regarding sample2 device, a maximum drain current I_{DS} = 925 mA/mm is obtained at a gate bias of 0 V and a drain bias of 5 V. An extrinsic peak transconductance (g_m) of approximately 250 mS/mm is measured at a gate bias of - 3.25 V for V_{DS} = 10 V. Typical output characteristics of sample2 device is shown in Fig. 2 and the corresponding transfer characteristics are given in Fig. 3

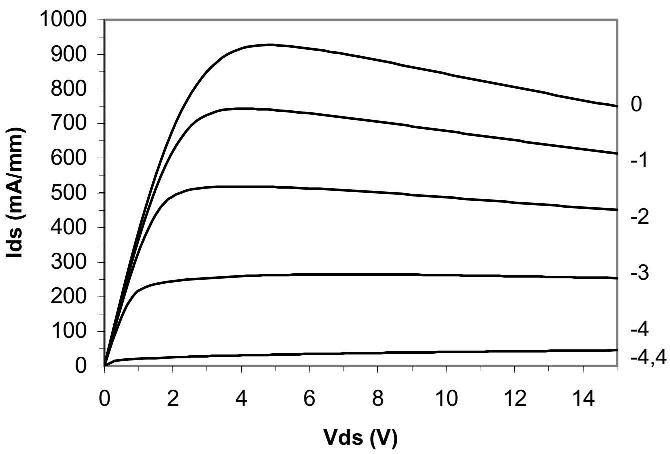

Fig. 2. Typical output characteristics of a 0.3 × 300 µm² sample2 device

It was noted that less current is measured on sample1 devices due to poor ohmic contact resistance value (2 Ω.mm) instead of 0.7 Ω.mm on sample2 device. These values are measured by the Transmission Line Method. The ohmic contact scattering contitutes a difficulty in the process of devices grown on silicon substrate.

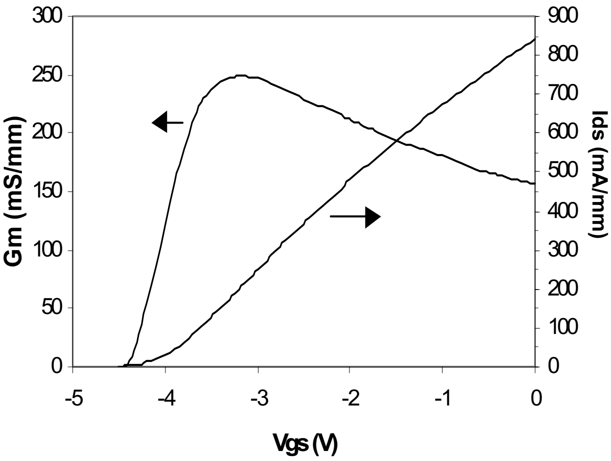

Fig. 3. Transfer characteristics of a 0.3 × 300 µm² sample2 device on a silicon substrate

RF measurement is performed on both epitaxial layers. The S-parameters are carried out using a HP8510C network analyzer connected to Picoprobe probes in the 0.5 to 50 GHz frequency range. The values of the unity current gain cutoff frequency (f_t) and the maximum frequency of oscillation (f_{max}) are determined by the extrapolation of the $|h_{21}|$ and Mason's gain using a -20dB/decade regression (see Fig. 4). In Fig. 5, the f_t and the f_{max} progression are shown versus drain current on sample1. In these measurements the drain was biased at 10 V, while the gate was biased between –3.4 V and 0.

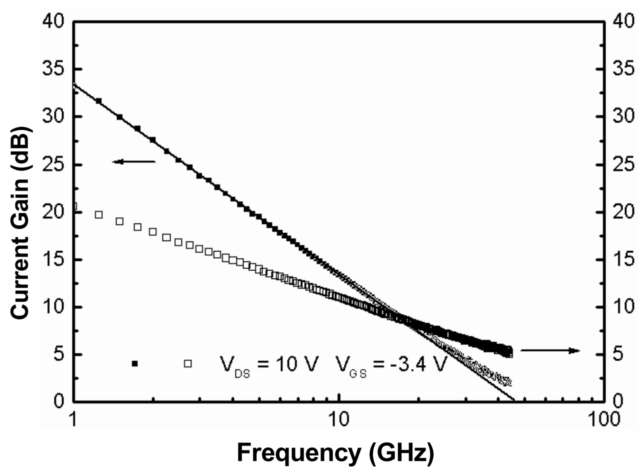

Fig. 4. Short circuit current gain ($|h_{21}|$) and maximum available gain (MAG) of 0.17×100µm² AlGaN/GaN HEMT on Si(111)

The intrinsic f_t, and f_{max} values are respectively 46 GHz and 92 GHz at V_{DS} = 10 V for the sample1 device, and 30 GHz, 72 GHz at V_{DS} = 15 V for the sample2 device. It is a good (f_{max} / f_t) ratio in both cases.

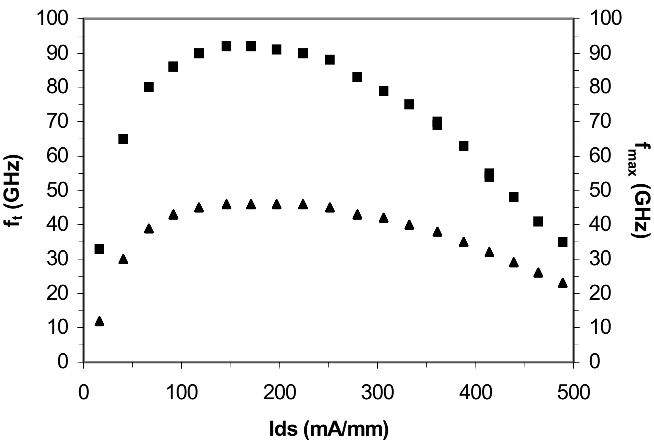

Fig. 5. f_t and f_{max} progression versus drain current on the sample1 device

The noise performance is measured on sample1 using a HP8570B noise figure meter, a HP8970B noise figure test set and a HP8510C Network Analyzer over 0.5 to 50 GHz frequency range.

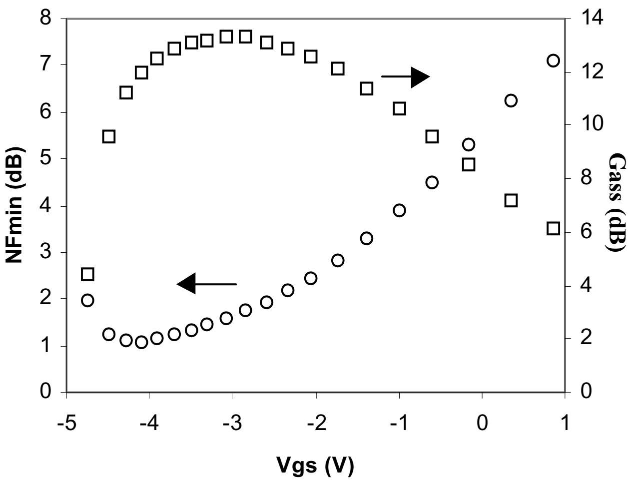

Fig. 6. Minimum noise figure and associated gain against gate bias for a 0.17 × 100 μm² sample1 device

Fig. 6 shows NF_{min} and G_{ass} measured at 10 GHz versus the gate bias. At V_{DS} = 10 V and V_{GS} = - 4.1 V, a minimum noise figure (NF_{min}) of 1.1 dB and an available associated gain (G_{ass}) of 12 dB are measured at 10 GHz.

Fig. 7. Shows NF_{min} and G_{ass} as a function of frequency. The straight line in this figure is a linear fit to the minimum noise figures measurements. For these measurements, devices were biased at V_{DS} = 10 V and I_{DS} = 92 mA/mm.

This shows that AlGaN/GaN HEMTs on silicon present a very interesting noise performance in the X-band. With conventional value of R_c (close to 0.5 Ω.mm), this devices could present a NF_{min} close to 0.8-dB at 10 GHz. To our knowledge, these results are the best NF_{min} associated to the highest G_{ass} for AlGaN/GaN HEMTs on silicon substrate.

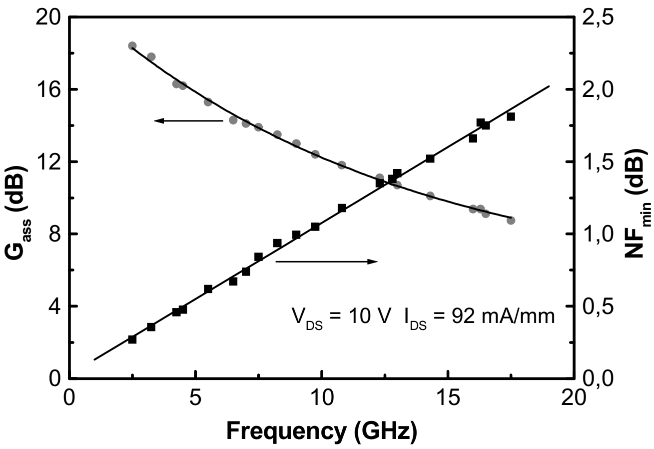

Fig. 7. Minimum noise figure and associated gain at 10 GHz versus frequency for a typical 0.17×100 μm² AlGaN/GaN HEMT

Large signal power measurements are also performed at 10 GHz on sample2, using on wafer load-pull and automated load-pull station with computer controlled mechanical tuners from Focus Microwaves.

At a drain voltage of 25 V and a gate voltage of –3 V corresponding to AB operating mode, an output power density of 1.7 W/mm was achieved at maximum PAE of 20 % associated to a linear gain of 13.7 dB.(see Fig. 8).

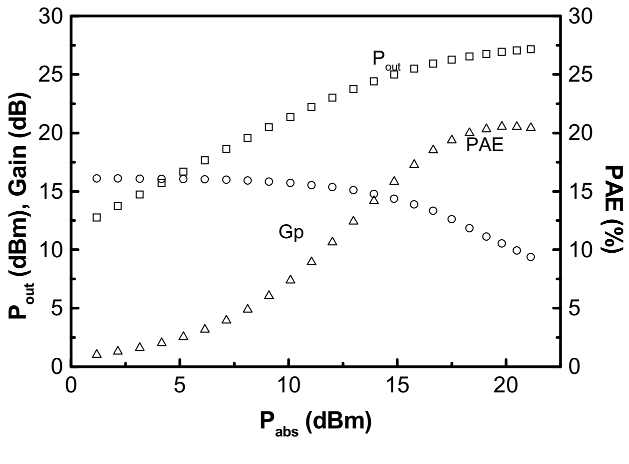

Fig. 8. HEMT power characteristics at 10 GHz for V_{DS} = 25 V (sample2)

Devices were then measured at V_{DS} = 30 V and V_{GS} = -3 V under class AB operation too. Devices show good performance. An output power density of 1.9 W/mm associated to a maximum power-added efficiency (PAE) of 18%, a linear gain of 16 dB and a power gain of 10 dB are measured. Fig. 9 shows the large signal performance of the 0.3 × 300 μm² sample2 device at 10 GHz. To our knowledge this output power density is the best result ever reported for AlGaN/GaN HEMTs on silicon substrates at this frequency.

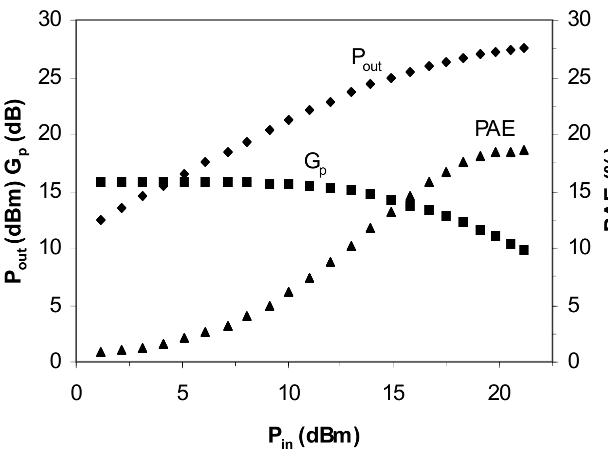

Fig. 9. HEMT power characteristics showing 1.9 W/mm at 10 GHz for a sample2 device.

As shown in Fig. 10, the saturated output power (P_{out}) increases gradually as a function of V_{DS} to 1,9 W/mm at V_{DS} = 30 V and f = 10 GHz.

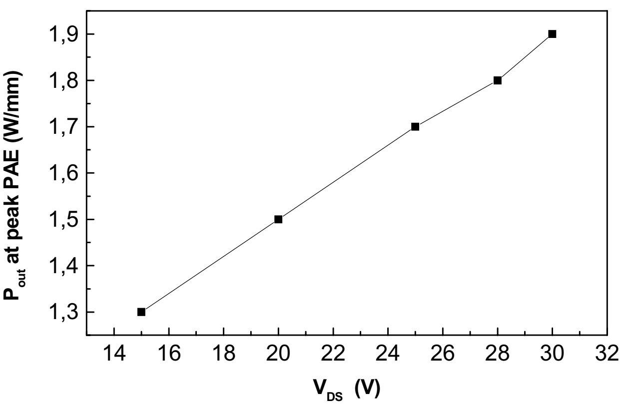

Fig. 10. Output power density at peak PAE as a function of drain bias measured at 10 GHz

IV. Conclusion

Low RF noise and high power performances are achieved on AlGaN/GaN HEMTs on silicon substrate. We want to emphasize that it is possible to obtain high performance on silicon substrate which is not naturally resistive. It is an interesting point because the silicon substrate is cheaper than SiC and Al_2O_3 substrates. Further improvements will lead to obtain these performances on the same device. Then, these AlGaN/GaN HEMTs will be excellent candidates for high power amplification and high sensibility low noise receivers in hard environment. Silicon substrates MMICs can be also investigated for the fabrication of HPA and LNA working in K-band.

V. Acknowledgements

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VI. References

[1] L.F. Eastman, “Experimental power and frequency limits of AlGaN/GaN HEMTs” *IEEE MTT-S Intl.Microwaves Symp.(IMS)* Seattle, 2002, pp. 2273-2275.

[2] W.L. Pribble, J.W. Palmour, S.T. Sheppard, R.P. Smith, S.T. Allen, T.J. Smith, Z. Ring, J.J. Sumakeris, A.W. Saxler, and J.W Milligan “Applications of SiC MESFETs and GaN HEMTs in power amplifiers”, *IEEE MTT-S Intl.Microwaves Symp.(IMS)* Seattle, 2002, pp. 1819-1822.

[3] R. Behtash, H. Tobler, P. Marschall, A. Schurr, H. Leier, Y. Cordier, F. Semond, F. Natali, J. Massies, “AlGaN/GaN HEMTs on Si (111) with 6.6 W/mm output power density” *IEE Electronics Letters.* Vol 39, N° 7, 2003, pp. 626-628.

[4] W. Lu, V. Kumar, R. Schwindt, E. Piner and I. Adesida “DC, RF and Microwave noise performances of AlGaN/GaN HEMTs on sapphire substrates” *IEEE transactions on microwave theory and techniques*, vol.50, N° 11, pp. 2499-2505.

[5] W. Lu, J. Yang, M.A. Khan and I. Adesida “AlGaN/GaN HEMTs on SiC with over 100 GHz f_T and Low Microwave Noise” *IEEE transactions on electron devices*, vol.48, N° 3, pp. 581-585.