RF Small-Signal and Power Characterization of AlGaN/GaN HEMTs

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S-parameter and load pull measurements are used to characterize the properties of AlGaN/GaN HEMTs grown on sapphire or silicon substrates. From the small signal data it follows that the cut-off frequencies f_T and f_{max} increase with the number of fingers, i.e. with the gate width, because of reduced contribution of parasitics to the total gate capacitance. Load-pull measurement setup is described and results of the output power, gain and PAE at 7 GHz are shown.

1. Introduction

It is well known that GaN based devices are useful for high frequency, high power and high temperature electronics. AlGaN/GaN high electron mobility transistors (HEMTs) with an output power density in the range of 1.5–11 W/mm at 2–20 GHz have been already demonstrated [1]. Thus, devices based on this material system are good candidates for RF-power amplifier application. However, various tasks related to the material structure [2] as well as device configuration (DC/RF dispersion, multi finger structures for high power operation, heat dissipation, long term stability, reproducibility, etc.) need to be solved to achieve wide applications of GaN based HEMTs.

Small signal (S-parameters) and power (load pull) measurements are presented in this study in order to characterize the properties of AlGaN/GaN HEMTs. Devices with various number of gate fingers, i.e. with different gate width, are used and the cut off frequencies f_T and f_{max} are evaluated. Principles of the load pull power measurements are described and results of the output power, gain and PAE at 7 GHz are shown.

2. AlGaN/GaN HEMTs

AlGaN/GaN heterostructures were prepared by LP-MOVPE growth on sapphire or silicon substrates. The device processing consisted of conventional HEMT fabrication steps and details can be found elsewhere [3]. Unpassivated multifinger devices with source-drain separation of 3 and 5 µm, gate length of 0.3 and 0.5 µm and gate width of 0.1, 0.2 and 0.3 mm (2, 4 and 6 fingers with 50 µm width each) were compared in this study.

3. Small-signal characterization

Linear networks operating with signals sufficiently small to cause the network to respond in a linear manner can be completely characterized by parameters measured at the network terminals (port) without regard of the content of the networks. S-parameters are important in RF design and easier to measure and work with at high frequencies than other kind of parameters. The ease of measuring and handling scattering parameters makes them especially well suited for describing the transistor properties.

Important figures of merit to describe the quality of a HEMT are the cutoff frequencies f_T and f_{max}. The current gain frequency f_T and the maximum frequency of oscillation f_{max} are determined as zero gain values of the current gain h_{21} and the unilateral gain GU, respectively. h_{21} and GU are calculated from measured S-parameters and using following equations:

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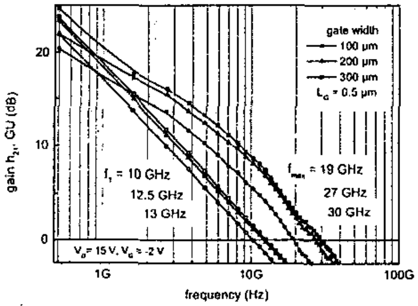

Fig. 1. Small signal performance of AlGaN/GaN HEMTs with different gate width.

$$h_{21} = \frac{-2S_{21}}{(1-S_{11})(1+S_{22})+S_{12}S_{21}},$$

and

$$GU = \frac{\frac{1}{2}\left|\frac{S_{21}}{S_{12}}-1\right|^2}{k\left|\frac{S_{21}}{S_{12}}\right| - \mathrm{Re}\left(\frac{S_{21}}{S_{12}}\right)}.$$

h_{21} and GU as a function of frequency were measured at different bias points to find optimal conditions. Results on AlGaN/GaN HEMTs on sapphire substrate are shown in Fig. 1. The devices were prepared simultaneously on the same wafer and differ only in the gate width. It is found that the cutoff frequencies f_T and f_{max} are enlarged by scaling up the gate width, i.e. by adding the gate fingers. Hence the device performance will be improved.

Device modeling based on the measured S-parameters was used to analyze observed f_T and f_{max} increase with increased gate width. This was done by means of the TOPAS Software tool from IMST, Kamp-Lintfort, Germany. The current gain frequency f_T can be expressed as $f_T = g_m/2\pi C_{GS}$, where g_m is the device transconductance and C_{GS} is the gate-source capacitance. From the equivalent circuit extracted g_m and C_{GS} as a function of the drain bias are shown in Fig. 2. A significant increase of both g_m and C_{GS} is found. By enlarging the gate width due to increasing the number of gate fingers the parasitic effect of the pads and stray capacitances decreases. For the f_T evaluation relevant g_m to C_{GS} ratio as a function of the drain bias is shown in Fig. 3. This result is in agreement with small-signal measurements and modeling of g_m to C_{GS} ratio as well as f_T increase significantly for the gate width increase from 100 to 200 µm but only slightly for 200 to 300 µm increase of the gate width.

Fig.2:

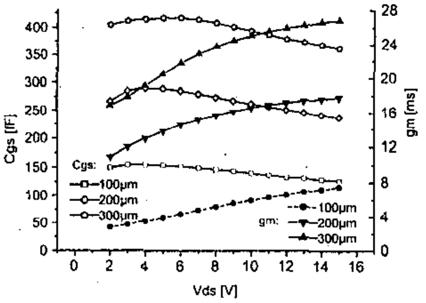

Fig.3

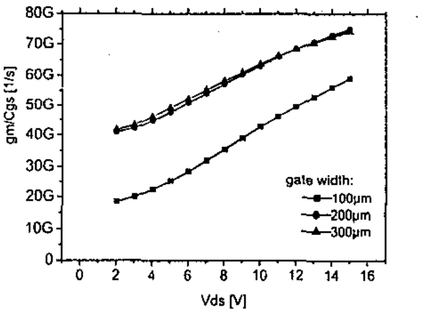

Fig. 2. Calculated C_{GS} and g_m as a function of the drain bias for different gate width.

Fig. 3. g_m to C_{GS} ratio as a function of the drain bias for differen t gate width.

4. Load-pull power measurements

Since AlGaN/GaN devices are suitable for power applications, power measurements and especially efficiency measurements at high frequencies will become a quality factor of these devices. The power added efficiency *PAE*,

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}},$$

is commonly evaluated together with the output power and gain. To measure the output power and PAE the input has to be matched and the losses at the input have to be calculated so that the power delivered to the input can be determined. The loading impedance becomes also important so that there must be a good matching provided at the output. In addition the power of the dc supply at the gate and the drain have to be measured.

Power measurements were performed by using an on-wafer load pull measurement system from FOCUS MICROWAVE, Quebec Canada. The schematic set up is shown in Fig. 4. Load pull is an impedance related measurement. It consists of an automatic controlled tuner system with electromechanical tuners at input and output of the device under test. The input power is delivered by a sweep generator, amplified, feed via isolator, input coupler, coaxial-switch and bias-tee, input and pre match tuner up to the probe tips at the device. Input and reflected power are measured at the input coupler. At the output of the device there are manual prematch tuner, automatic output tuner, bias-tee, coaxial switch and output power meter. Each impedance position of the input and output tuners has to be calibrated for each single operated frequency. Under large signal condition we have a non-linear behavior of the device.

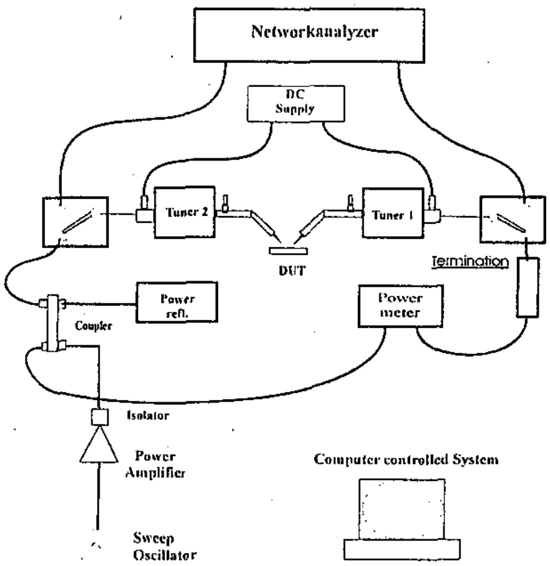

Figure 4. Load pull measurement setup.

First results of our power measurements on AlGaN/GaN HEMTs are demonstrated in Fig. 5. The output power P_{out}, gain and power added efficiency *PAE* as a function of the input power P_{in} are evaluated. These data were obtained at the frequency of 7 GHz and the DC bias conditions were: the drain voltage V_{DS} = 10V and the gate voltage V_{GS} = -4V. The *PAE* shows a maximum at about 20%. Values of up to 32% have been reported recently [1], however using devices on high resistive SiC substrates in contradiction to sapphire. SiC is less lattice mismatched to GaN (better material quality can be expected) and has higher thermal conductivity than sapphire. Unfortunately, the price of SiC substrates is extremely high and therefore AlGaN/GaN HEMTs on silicon [3] (cheep and large area wafers available, mediate thermal conductivity) seem to be an optimal alternative concerning device performance and costs to be used in general purpose applications.

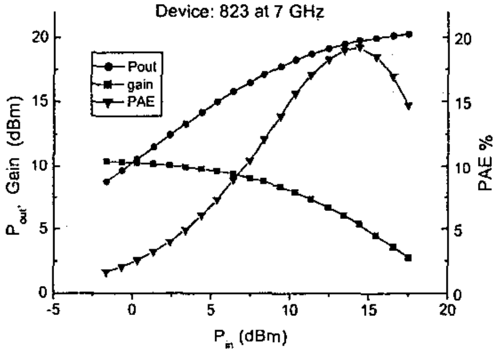

Figure 5. Power and PAE measurements on an AlGaN/GaN HEMT at 7 GHz.

5. Conclusions

Small signal (S-parameters) and power (load pull) measurements on AlGaN/GaN HEMTs were presented. Devices with different gate width, were studied. From the small signal data and simulations it has been found that the cut off frequencies f_T and f_{max} increase with the number of fingers, i.e. with the gate width, because of reduced contribution of parasitics to the total gate capacitance. Principles of the load pull power measurements and used setup have been described and results of the output power, gain and PAE obtained at 7 GHz on AlGaN/GaN HEMTs were described.

References :

[1] Book of abstracts, 3^{rd} *Intern. Workshop on Nitride Semic.*, Aachen, D, 22.07.-25.07.2002, Research Centre Jülich (2002)

[2] P. Kordos, *Proc. 3^{rd} Intern. Conf. ASDAM'2000*, pp. 47-54 (2000)

[3] P. Javorka et al., *IEEE Electron Device. Lett.* **23**, 4 (2002)