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ADVANCED LARGE-SIGNAL MODELING OF GaN-HEMTs

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Abstract

For improved non-linear modeling of AlGaN/GaN high electron mobility transistors, a large-signal model originally developed for GaAs-based devices has been extended by introduction of a thermal sub-circuit to account for self-heating. Thereby, DC output characteristics which typically show negative output conductance at a high dissipating power level are well reproduced. Since self-heating also effects the transconductance, which is related to S_{21} at RF conditions, the comparison of broadband S-parameter simulations and measurements revealed significant improvement when using the extended model. First experimental and theoretical investigations on the transient behavior at pulsed conditions are finally presented.

I. Introduction

In recent years, AlGaN/GaN high electron mobility transistors (HEMTs) have been developed and investigated in detail due to the high potential of this materials system for high power, high frequency and high temperature electronics (see, e.g., [1]). It is expected that for many applications, e.g. base-station amplifiers or radar, nitride-based transistors and circuitry play an important role in the near future. Power amplifier and circuit design requires adequate modeling of the transistor behavior at its various operating conditions such as DC, cw-RF and pulsed mode. Under each operating condition, the responding behavior of the transistor is differently influenced by thermal effects introduced by poor thermal conductivity of the adjacent substrate. This in particular shows up when sapphire having a thermal conductivity of 0.4 W/cmK is used as a substrate instead of SiC (4.5 W/cmK). The SiC substrate appears to be the substrate of choice (moreover due to better lattice constants match), however, its significantly higher price might prevent from use for mass products. Therefore, consideration of substrate-induced thermal effects is required for comprehensive modeling of the transistor (note that although in use of SiC substrates thermal effects appear at high dissipating power levels [2]). In nitride-based HEMTs, beside thermal effects, trap-related dispersion may also give rise to discrepancies between static and dynamic characteristics [3]. So far, to the best of our knowledge, papers reporting on large-signal modeling of AlGaN/GaN-HEMTs are scarce [4, 5]. This paper presents non-linear modeling results obtained by an extension of an existing large-signal model [6-8] to account for self-heating effects. Simulations are compared with DC and broadband S-parameter measurements for validation purposes. Finally, first experimental investigations under pulsed stimulus are presented and discussed in regard to further verification of the improved model.

II. Theoretical description of the large-signal model

As a starting point for GaN HEMT modeling including self-heating, the analytical large-signal transistor model developed for GaAs HEMTs [6-8] has been chosen because of its simple model equations yet excellent non-linear modelling capabilities. This original model was implemented as a user-defined model in Agilent Advanced Design System (ADS) and has already been applied for AlGaN/GaN-HEMTs. Although dynamic output characteristics were used for the parameter extraction, the first attempt shows the necessity of the self-heating correction [9]. The original large-signal equivalent circuit is divided into two parts – the internal transistor with its non-linear elements and the parasitic network. The parameters of the parasitic network are determined from "Cold" S-parameter measurements [10]. For the internal transistor, a drain current source and two current sources representing the gate current as well as two non-linear capacitances are used to model its non-linear behavior.

According to Wei et al. [11], the large-signal equivalent circuit is extended by an additional thermal sub-circuit (see Figure 1). The thermal sub-circuit consists of the parallel connection of the current source, i_{th}, the thermal resistance, R_{th}, and the thermal capacitance, C_{th}, which describe the self-heating-related decrease of the current. In the simulation procedure, both the thermal sub-circuit and the transistor equivalent circuit are jointly considered.

As follows, the basic model equations are summarized:

The thermal current source represents dissipating power in the device

$$i_{th} = I_{ds} V_{dsi} \tag{1}$$

and the voltage drop on the thermal resistance gives the channel temperature rise

$$\Delta T = R_{th} i_{th} = R_{th} I_{ds} V_{dsi} . \tag{2}$$

This channel temperature rise ΔT leading to the drain current decrease at high dissipated power level gives an additional term (f_4) in the basic drain current source equation:

$$I_{ds}\left(V_{gsi}, V_{dsi}\right) = f_1\left(V_{gsi}\right) \cdot f_2\left(V_{gsi}, V_{dsi}\right) \cdot f_3\left(V_{dsi}\right) \cdot f_4\left(\Delta T\right) \tag{3}$$

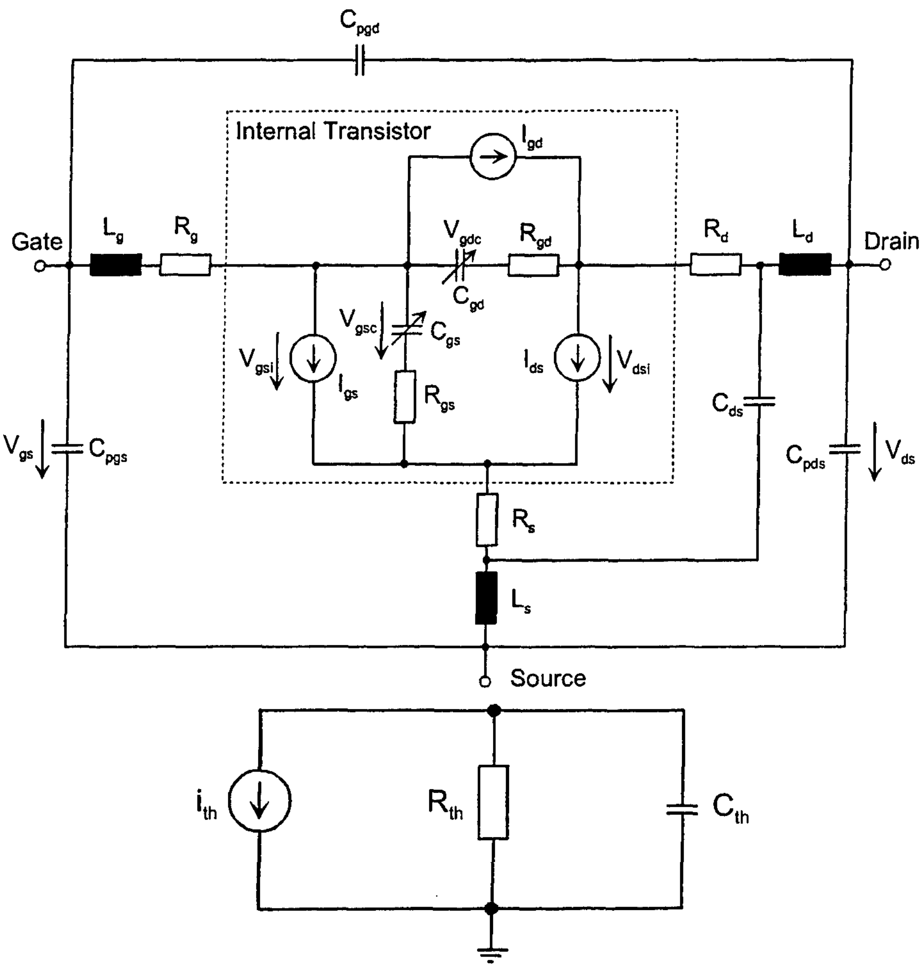


Figure 1: Large-signal equivalent circuit of the GaN HEMT with thermal sub-circuit

$$f_4(\Delta T) = 1 - \kappa \frac{\Delta T}{T_0} \tag{4}$$

where T_0 is the ambient temperature; κ parameter.

The basic terms of the original model are

$$f_1\left(V_{gsi}\right)=CD_{vc}\cdot\left(1+\tanh\left[\beta\cdot\left(V_{gsi}-V_c\right)+\gamma\cdot\left(V_{gsi}-V_c\right)^3\right]\right)$$
$$+CD_{vsb}\cdot\left(1+\tanh\left[\delta\cdot\left(V_{gsi}-V_{sb}\right)\right]\right) \quad , \qquad (5)$$

$$f_2\left(V_{gsi},V_{dsi}\right)=1+\frac{\lambda}{1+\Delta_\lambda\cdot\left(V_{gsi}-V_{to}\right)^2}\cdot V_{dsi}, \quad \text{with} \quad V_{to}=V_c-\frac{2}{\beta}, \qquad (6)$$

and

$$f_3\left(V_{dsi}\right)=\tanh\left(\alpha\cdot V_{dsi}\right), \quad \text{with} \quad \alpha=\frac{\alpha_0}{1+KV_{gs}} \quad . \qquad (7)$$

f_1 describes the transfer behavior of the transistor, f_2 models the RF output conductance and f_3 the triode region.

The part of the original model responsible for the triode region of the transistor output characteristics (f_3) is also modified by an additional parameter K to include the dependence of the slope on the gate voltage.

Note that the low-pass characteristic of the thermal sub-circuit reflects the frequency dependence of the self-heating (i.e., current reduction). It means that the transition to high frequency stimulus, where self-heating cannot follow anymore, is considered. For transient behavior, the respective time constant is

$$\tau = R_{th}\,C_{th} \ . \qquad (8)$$

III. Experiment

The transistor structures were grown by metal organic vapor phase epitaxy on sapphire substrate and consisted of a AlN-nucleation / GaN-buffer / Al(0.24)Ga(0.76)N-barrier / GaN-cap layer sequence (5 nm/1,6 µm/24 nm/3 nm) (Figure 2). A composition of Ti/Al/Au (20 nm/120 nm/200 nm) is used for the ohmic contacts, which has been alloyed at 870 °C for 45 s by RTA. The gate consists of a standard Ni/Au (100 nm/150 nm) Schottky diode without any temperature treatment after the metalization process. The herein presented results have been obtained from a device with a gate length and width of 1,5 μm and 2×100 μm, respectively. Standard bias-dependent broad-band S-parameter measurements up to 40 GHz have been performed at room temperature. For pulsed measurements, a LeCroy LC 584A digital oscilloscope has been used.

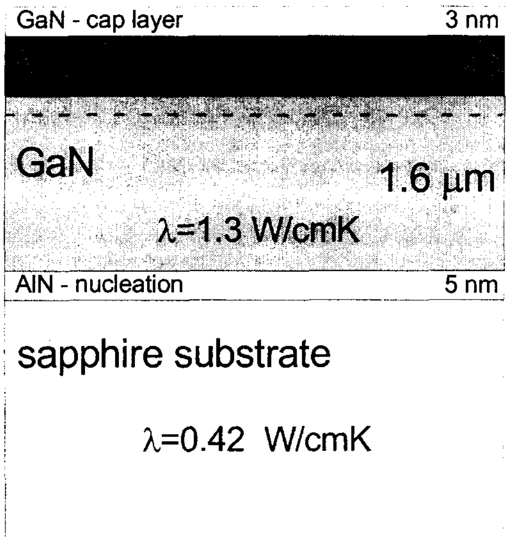


Figure 2: Sketch of a typical AlGaN/GaN/sapphire-substrate-HEMT structure indicating thermal properties

IV. Results

Figure 3 depicts measured and simulated DC output characteristics of the HEMT. Experimentally, a negative output conductance is clearly observed at increased dissipating power (i.e. at increased $I_{ds}V_{ds}$) as a direct consequence of the elevated channel temperature. Simulations by the original model (Figure 3a.) do not allow to reproduce the negative slope. Instead, by applying the improved model equations described in section II, a very good agreement of measured and simulated characteristics has been achieved. The average error of 5% validates the improved approach.

Respective advances have been achieved in S-parameter simulations including the thermal sub-circuit as shown in Figure 4. For S_{21}, discrepancies of measured and simulated data at low frequencies which arise due to self-heating-related reduction of the transconduction have been overcome in the improved approach. Here, the average errors of measured and simulated S-parameters of about 10% are satisfactorily low.

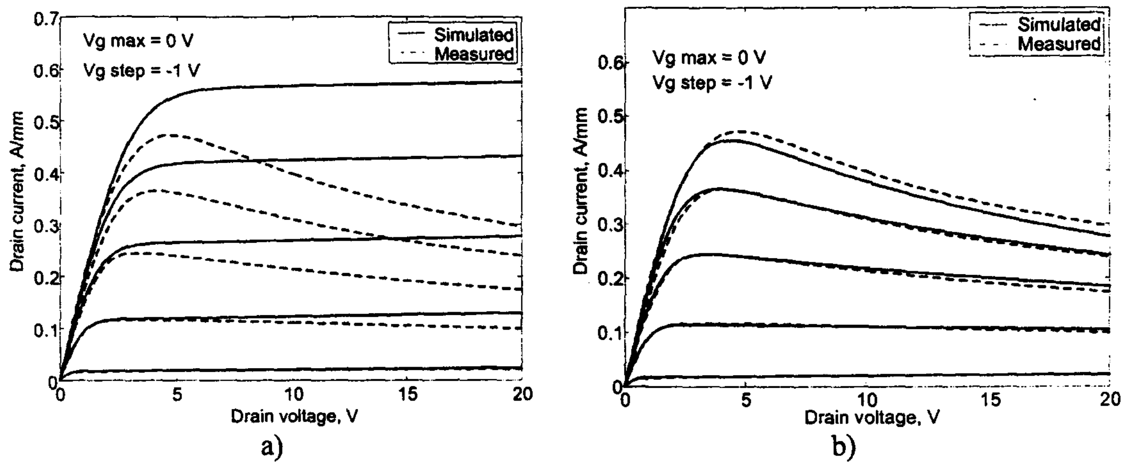


Figure 3: Measured and simulated output characteristics using the large-signal model without (a) and with (b) thermal effect

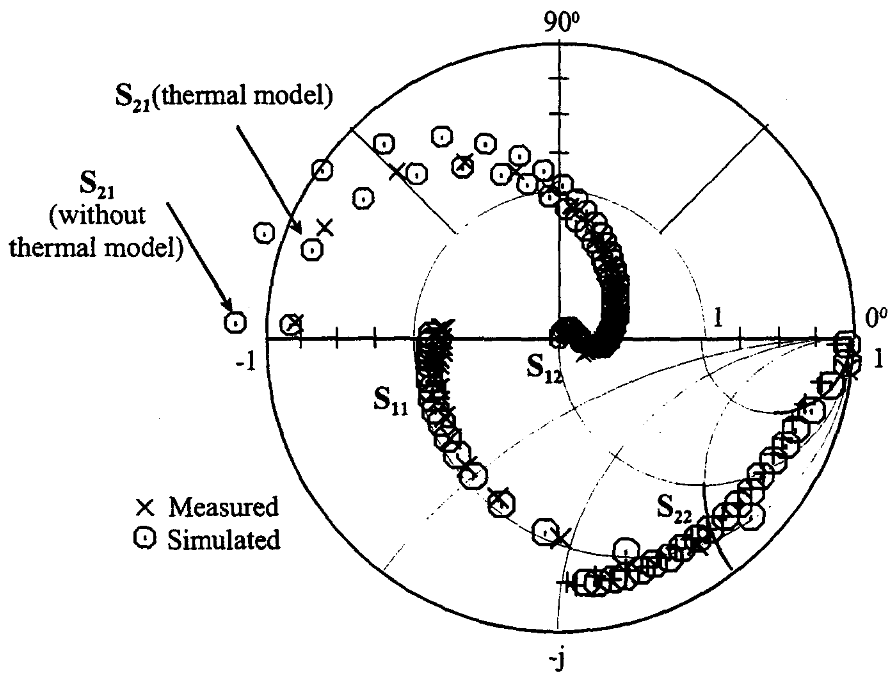
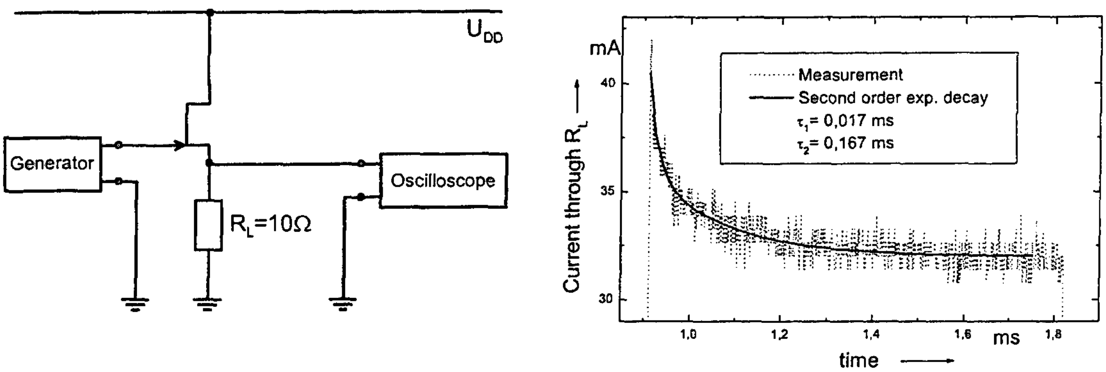


Figure 4: Measured and simulated S-parameters (S_{21} simulated without thermal effect is also shown).

The improved model has finally been examined for predictions of the transient behavior under pulsed stimulus. For this, rectangular shaped gate-source-voltage-pulses from pinch-off (-8 V) to open-channel condition (0 V) at a 0.55 kHz repetition rate have been applied at constant drain-source-voltage. The voltage drop over a R_L = 10 Ω resistance, connected to the source, was measured. Connection of the resistor in the source line of the transistor (Figure 5a) instead of connection in the drain line was used in order to simplify the measurement technique (no differential measurements were necessary). We note that the respective current through R_L is therefore not the drain-current, but the sum of drain-current and gate-current. Since the transient time of the gate-current is much smaller than the thermal transient time (ps vs. ms), the influence of the gate-current is negligible. Detailed inspection of the experimental traces shows that two thermal time constants govern the fall of the drain current (Figure 5b). This is explained by the layered structure of the device where the layers of dominant thickness (2 µm GaN buffer and 500 µm sapphire substrate) have various thermal conductivities (see Figure 2). This explanation is sustained by similar investigations which have been published recently [12].



a) b)

Figure 5: Experimental setup (a) and drain-current transient at pulsed stimulus (V_{gs} from −8 V to 0 V at constant V_{ds} = 20 V), including second order exponential decay fitting (b)

V. Conclusion

An adequate extension of a large-signal model to account for self-heating related deterioration of the transistor behavior has been presented. Both DC and S-parameter simulations compare very well with experimental data, thus validating that the advanced model is capable to comprehensively describe the transistor behavior under such conditions. By using the improved model, experimental results obtained under pulsed conditions have additionally been compared to simulations. It turned out that two different time constants, most likely originating from the different thermal conductivities of the GaN buffer layer and the sapphire substrate, govern the transient behavior of the device. A second pair of thermal resistance and capacitance has to be connected to the thermal sub-circuit, to reflect two measured time constants. The advanced large-signal model will sufficiently provide improved predictions of broadband amplifier performance and nitride-based circuit design.

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