# A new empirical nonlinear model for HEMT-devices

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## Abstract

A new large signal model for HEMTs, capable of modeling the current-voltage characteristic, and its derivatives, including the characteristic transconductance peak, gate-source- and gate-drain- capacitances is described. Model parameter extraction is straightforward and is made for a submicron gate-length ∂-doped pseudomorphic HEMT. Measured and modeled DC- and S-parameters are compared.

## Introduction

Different empirical models suitable for simulation of GaAs MESFETs in nonlinear circuits have been developed [1-5]. Some of the models have been incorporated in commercial Harmonic Balance (HB) simulators. These models are used to predict gain, intermodulation distortion, generation of harmonics, etc, versus bias for circuits like amplifiers, mixers, and multipliers. Recently, Maas et al [5] pointed out that not only the current-voltage characteristic $I_d[V_{gs},V_{ds}]$ but also the derivatives have to be modeled correctly, especially if the model is supposed to predict intermodulation distortion. In [5], the $I_d[V_{gs}]$ dependence is modeled as a harmonic series, and the coefficients are fitted to both the measured $I_d[V_{gs},V_{ds}]$ and its derivatives by using singular-value decomposition.

Since the above models are intended mainly to describe the performance of MESFETs, there are increasing demands for HEMT models, which can model the characteristic peak in the transconductance found in most HEMTs. In principle, the model utilized in [5] could be used, but many terms are normally needed and parameter extraction must be done by special techniques.

We propose a simple model, where parameter extraction can be made by simple inspection of the experimental $I_d[V_{gs},V_{ds}]$ and $g_m[V_{gs}]$ characteristics, yet it models $I_d$ and its derivatives with good accuracy. The model has been applied to both ordinary AlGaAs-GaAs and pseudomorphic AlGaAs-InGaAs-GaAs HEMTs with good results.

## The model

The drain current function is expressed in accordance with previous models as

$$I_d[V_{gs},V_{ds}]=I_{dA}[V_{gs}]\,I_{dB}[V_{ds}] \qquad (1)$$

where the first term is dependent only on the gate voltage and the second only on the drain voltage. The $I_{dB}[V_{ds}]$ term is the same as the one used in other models [1,3]. For $I_{dA}[V_{gs}]$, however, we propose to use a function whose first derivative has the same 'bell shaped' structure as the measured transconductance function $g_m[V_{gs}]$. The **tanh** function was chosen since this function describes the gate voltage dependencies and its derivatives well and is normally available in commercial HB-simulators i.e.

$$I_d=I_{pk}(1+\tanh(\psi))(1+\lambda V_d)\tanh(\alpha V_d) \qquad (2)$$

where $I_{pk}$ is the drain current, with the contribution from the output conductance subtracted, at which we have maximum transconductance and $V_{pk}$ is the corresponding gate voltage. $\lambda$ is the channel length modulation parameter and $\alpha$ is the saturation voltage parameter. Parameters $\alpha$ and $\lambda$ are the same as those used in the Statz and Curtice model. $\psi$ is in general a power series function centred at $V_{pk}$ with $V_{gs}$ as a variable i.e.

$$\psi=P_1(V_{gs}-V_{pk})+P_2(V_{gs}-V_{pk})^2+P_3(V_{gs}-V_{pk})^3+\ldots \qquad (3)$$

The selected $I_d[V_{gs},V_{ds}]$ function has well defined derivatives. An advantage of the selected model is its simplicity. The different parameters can as a first approximation be easily obtained by inspection of the measured $I_d[V_{gs},V_{ds}]$ at a saturated channel condition as follows: all higher terms in $\Psi$ are as

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sumed to be zero, $\lambda$ is determined from the slope of the $I_d$-$V_d$ characteristic, $I_{pk}$ and $V_{pk}$ are determined at the peak transconductance, $g_{mpk}$. $P_1$ is now obtained as

$$P_1=g_{mpk}/(I_{pk}(1+\lambda V_d)) \approx g_{mpk}/I_{pk} \quad (4)$$

In some of the HEMTs there is a weak variation of $V_{pk}$ on the drain voltage $V_d$. This can be taken into the account as:

$$V_{pk}=V_{pko} + \gamma \cdot V_d \quad (5)$$

the same type of modeling functions were chosen o model the dependencies on gate and drain voltage of the capacitances $C_{gs}$ and $C_{gd}$

$$C[V_{gs},V_{ds}]=C_A[\tanh(V_{gs})]\, C_B[\tanh(V_{ds})] \quad (6)$$

as suggested by [6,7]. Due to the similarity of $I_d[V_{gs},V_{ds}]$ and $C_{gs}[V_{gs},V_{ds}]$ the functions can be expressed as

$$C_{gs}=C_{gso}[1+\tanh(\psi_1)][1+\tanh(\psi_2)] \quad (7)$$

$$C_{gd}=C_{gdo}[1+\tanh(\psi_3)][1-\tanh(\psi_4)] \quad (8)$$

where

$$\Psi_1=P_{ogsg}+P_{1gsg}V_{gs}+P_{2gsg}V_{gs}^2+P_{3gsg}V_{gs}^3+.... \quad (9)$$

$$\Psi_2=P_{ogsd}+P_{1gsd}V_{ds}+P_{2gsd}V_{ds}^2+P_{3gsd}V_{ds}^3+.... \quad (10)$$

$$\Psi_3=P_{ogdg}+P_{1gdg}V_{gs}+P_{2gdg}V_{gs}^2+P_{3gdg}V_{gs}^3+.... \quad (11)$$

$$\Psi_4=P_{ogdd}+(P_{1gdd}+P_{1cc}V_{gs})V_{ds}+P_{2gdd}V_{ds}^2+ P_{3gdd}V_{ds}^3+.... \quad (12)$$

The term $P_{1cc}V_{gs}V_{ds}$ reflects the cross-coupling of $V_{gs}$ and $V_{gd}$ on the $C_{gd}$. When an accuracy of the order of 5-10% of the $C_{gs}$ and $C_{gd}$ is sufficient equations (3)-(8) can be simplified to:

$$C_{gs}=C_{gso}[1+\tanh(P_{1gsg}V_{gs})][1+\tanh(P_{1gsd}V_{ds})] \quad (13)$$

$$C_{gd}=C_{gdo}[1+\tanh(P_{1gdg}V_{gs})] [1-\tanh(P_{1gdd}V_{ds}+P_{1cc}V_{gs}V_{ds})] \quad (14)$$

Equation 14 can be further simplified if cross-coupling at large drain voltages ($V_{ds}$>1 V) is neglected:

$$C_{gd}=C_{gdo}[1+\tanh(P_{1gdg}V_{gs})] [1-\tanh(P_{1gdd}V_{ds})] \quad (15)$$

This is valid for the $\delta$-doped HEMTs with an undoped AlGaAs spacer-layer used in this study since

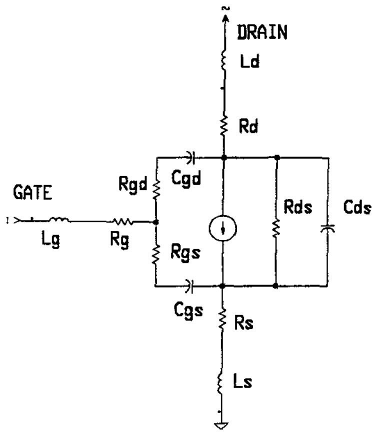


Fig. 1: The equivalent circuit of the transistor.

they have a saturated $C_{gs}[V_g]$ characteristic for increasing $V_g$ due to absence of parasitic MESFET channel formation in the AlGaAs layer, found in HEMTs with a doped AlGaAs layer.

## Experimental verification

The model parameters were extracted for different pulse-doped pseudomorphic HEMTs with gate length from 0.12 µm to 0.35 µm and gate width from 50 µm to 200 µm, fabricated in our laboratory. DC-parameters were measured by using a HP 4145B parameter analyzer and S-parameters were measured by Cascade probes WPH-405 connected to a Wiltron 360 Vector Network Analyzer in the frequency range 0.5-62.5 GHz. All of the measured HEMTs have very low $S_{12}$-parameter at normal bias conditions. Here we present results of measurements of the HEMTs with the gate width of 0.35 µm and gate length 200 µm for which accuracy of measurements of the S-parameters is higher. S-parameters were measured at the following bias points for parameter extraction: $V_d$=-1 V, -0.5 V, 0 V, 0.75 V, 2 V, 3 V and.$V_g$=-1.5 V- +0.5 V with a step of 0.25 V. Negative drain voltages are important for drain mixers. The parasitic parameters of the transistor (fig. 1) can be found most accurately at $V_d$=0. This regime is also important for mixers working in the resistive mode [8]. At $V_{ds}$=0.75 V $I_{ds}$ is saturated and at $V_{ds}$=2-3 V the transistor is in its normal operating mode.

The intrinsic parameters of the equivalent circuit (Fig. 1) were derived. The parasitic parameters $L_g$, $L_d$, $L_s$, $R_g$, $R_d$, $C_p$ were fixed and not changed during optimization. At negative drain voltage the sign of the conductance is reversed.

Our model was easily implemented in a commercial Harmonic Balance-simulator (MDS from HP) as a custom defined equation model. The model parameters are listed in Table 1.

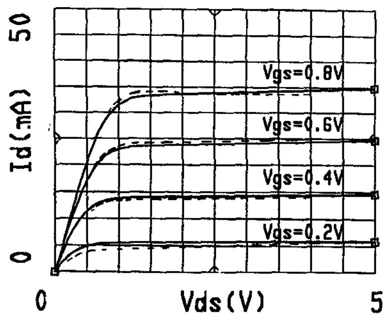


Fig. 2a: Measured (dots) and modeled (solid lines) drain current, $I_d$ vs gate voltage, $V_{gs}$.

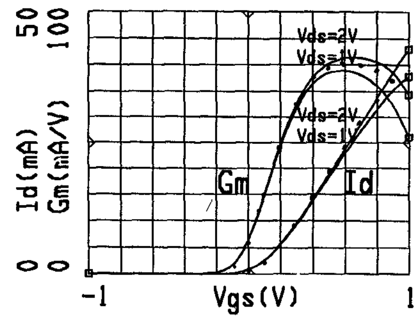


Fig. 2b: Measured (dots) and modeled (solid lines) drain current, $I_d$ and transconductance, $g_m$ vs gate voltage, $V_{gs}$.

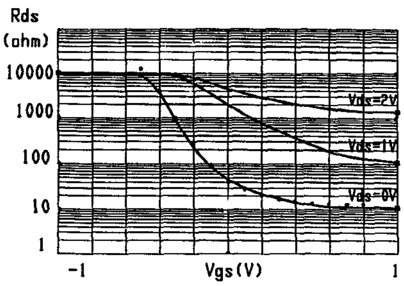


Fig. 2c: Measured (dots) and modeled (solid lines) Drain resistance, $R_{ds}$ vs gate voltage, $V_{gs}$.

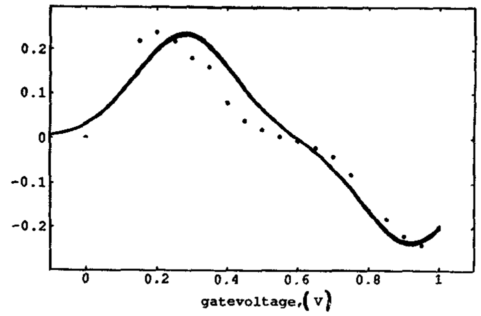


Fig. 2d: Measured (dots) and modeled (solid lines) derivative of transconductance $d(g_m)/dV_g$.

In its simplest form $\psi = P_1(V_{gs}-V_{pk})$. It is, however, recommended for this particular HEMT to include the cubic term in order to improve the fitting of the drain current and its derivates at voltages close to pinch-off. All terms except $P_1$ and $P_3$ are zero.

In Figure 2 a, b, c and d, the measured and modeled $I_d$-$V_d$ characteristics, transconductance $g_m$, output resistance and the derivative of $g_m$ are shown respectively.

Fig. 3 shows the measured and simulated magnitude of $S_{21}$ of the transistor at different bias points. $S_{21}$ is shown in greater detail because of its sensitivity to bias conditions. The difference between the modeled and simulated values is very small.

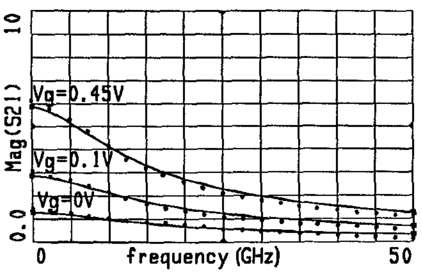


Fig. 3: The simulated (solid lines) and measured (dots) magnitude of $S_{21}$ of the HEMT.

Figures 4 a, b and c show the measured and modeled dependencies of $C_{gs}$ and $C_{gd}$ for transistors with gate widths of 200 µm x 0.35 µm. It can be seen, that the most often used models (pn-junction or Statz models ) are not workable in this case. For this type of a pulse-doped pseudomorphic HEMT following simple expressions were found (with simple curve fitting procedure [9] ) giving accuracy, which is sufficient for most practical cases:

$$C_{gs}=C_{gso}\left[1+\tanh\left(V_{gs}-0.048V_{gs}^2\right)\right]\left[1+\tanh(0.4V_{ds})\right] \quad (16)$$

$$C_{gd}=C_{gdo}\left[1+\tanh\left(0.48V_{gs}\right)\right]\left[1-\tanh\left(0.55V_{ds}-0.048V_{ds}^2+0.2V_{gs}V_{ds}\right)\right] \quad (17)$$

and for the simplified equation of Cgd we obtain:

$$C_{gd}=C_{gdo}\left[1+\tanh(0.48V_{gs})\right]\left[1-\tanh(0.55V_{ds})\right] \quad (18)$$

where $C_{gso}=C_{gdo}=145$ fF are the capacitances for $V_{gs}=V_{ds}=0$.

In fig. 4b and c modeled dependencies of $C_{gd}$ using equation (17) and (18) are shown. Evidently even such a simple equation as (18) gives very good accuracy. When higher accuracy is required more terms should be included in the model.

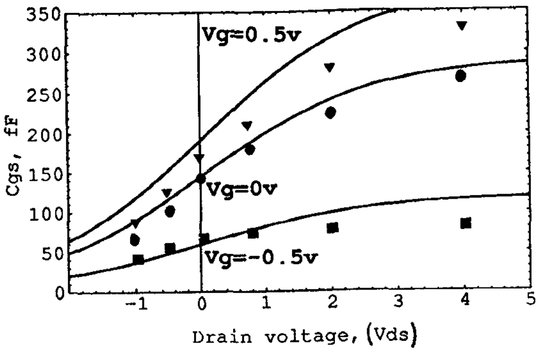


Fig. 4a: Measured (dots) and modeled (solid lines) $C_{gs}$ vs $V_{ds}$ according to eq. (16).

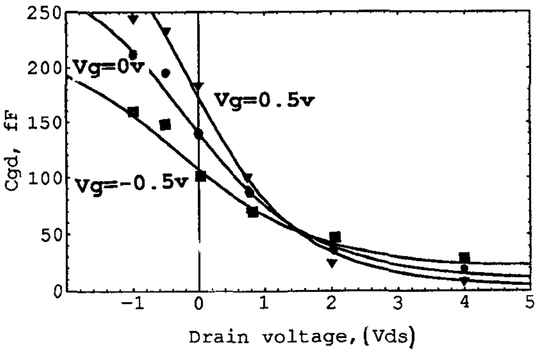


Fig. 4b: Measured (dots) and modeled (solid lines) $C_{gd}$ vs $V_{ds}$ according to eq. (17).

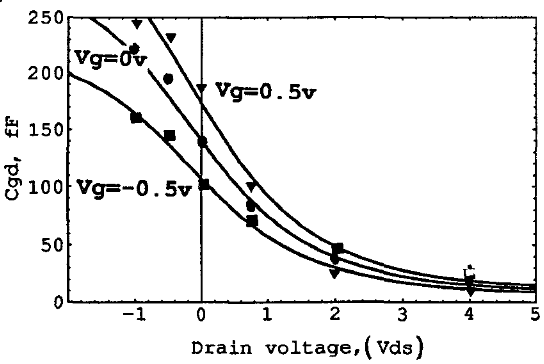


Fig. 4c: Measured (dots) and modeled (solid lines) $C_{gd}$ vs $V_{gs}$ according to eq. (18).

## Conclusions

A practical and simple but yet accurate large-signal empiric model capable of modeling the drain current-gate voltage characteristic and its derivatives, and the capacitances $C_{gs}$ and $C_{gd}$ for HEMTs is presented. Parameter extraction and the incorporation of this model into a commercial software tool is straightforward The model has been used to predict the DC- and S-parameters of the devices and different nonlinear circuits like mixers and multipliers with very high accuracy.


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Table 1: Extracted parameters of the HEMT.

| $R_g$ [Ω] | $R_{gs}$ [Ω] | $R_s$ [Ω] | $R_f$ [Ω] | $R_d$ [Ω] | $R_{ds}$ [Ω] | $C_{ds}$ [fF] | $C_{rf}$ [pF] | $C_{gs}$ [pF] | $C_{gd}$ [fF] |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 3.5 | 3 | 4 | 6 | 1200 | 60 | 100 | 0.28 | 35 |

| $I_{pk}$ [mA] | $P_1$ | $P_3$ | $V_{pk}$ [V] | λ | α |
|---|---|---|---|---|---|
| 26.3 | 3.05 | 7 | 0.55 | 0.02 | 3 |

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