A New Empirical Nonlinear Model for HEMT and MESFET Devices

IlΊcho Angelov, Herbert Zirath, and Niklas Rorsman

Abstract—A new large signal model for HEMT's and MESFET's, 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 demonstrated for different submicron gate-length HEMT devices including different δ-doped pseudomorphic HEMTs on GaAs and lattice matched to InP, and a commercially available MESFET. Measured and modeled dc and S-parameters are compared and found to coincide well.

INTRODUCTION

DIFFERENT empirical models suitable for simulation of GaAs MESFETS in nonlinear circuits have been developed [1]–[6]. 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. [6] pointed out that not only the current-voltage characteristic \( I_{ds}(V_{gs}, V_{d}) \) but also their derivatives have to be modeled correctly, especially if the model is supposed to predict intermodulation distortion. In [6], the \( I_{ds}(V_{gs}) \) dependence is modeled as a harmonic series, and the coefficients are fitted to both the measured \( I_{ds}(V_{gs}, V_{d}) \) 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 general FET models, which model both HEMTs and MESFETs. In particular, the characteristic peak in the transconductance versus gate voltage dependence found in most HEMTs must be correctly modeled. In principle, the model utilized in [2], [6] could be used, but many terms are normally needed and parameter extraction requires special techniques.

We propose a new simple model, where parameter extraction can be made by simple inspection of the experimental \( I_{ds}(V_{gs}, V_{d}) \) and \( g_m(V_{gs}) \) dc-characteristics, which models \( I_{ds} \) and its derivatives with good accuracy. The model has been applied to FETs based on the following material structures: AlGaAs-GaAs, pseudomorphic (AlGaAs-InGaAs-GaAs) (homogeneously doped and single and double δ-doped), lattice matched to InP (AlInAs-GaInAs-InP), and GaAs MESFET's with good results.

\( I_{ds}(V_{gs}, V_{d}) = I_{ds0}(V_{gs}) I_{db}(V_{d}) \) (1)

where the first factor is dependent only on the gate voltage and the second only on the drain voltage. The \( I_{db}(V_{d}) \) term is the same as the one used in other models [1], [4]. For \( I_{ds0}(V_{gs}) \), however, we propose a function whose first derivative has the same bell shaped structure as the measured transconductance function \( g_m(V_{gs}) \). The hyperbolic tangent (tanh) function describes the gate voltage dependencies and its derivatives well and is normally available in commercial HB-simulators i.e.:

\( I_{ds} = I_{pk}(1 + \tanh(\psi))(1 + \lambda V_{ds}) \tanh(\alpha V_{ds}) \) (2)

where \( I_{pk} \) is the drain current at which we have maximum transconductance, with the contribution from the output conductance subtracted. \( \lambda \) is the channel length modulation parameter and \( \alpha \) is the saturation voltage parameter. The parameters \( \alpha \) and \( \lambda \) are the same as those in the Statz and Curtice models. \( \psi \) is in general a power series function centered at \( V_{gs} \) with \( V_{gs} \) as a variable i.e.

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

where \( V_{pk} \) is the gate voltage for maximum transconductance \( g_{mpk} \). The selected \( I_{ds0}(V_{gs}, V_{d}) \) 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 \( I_{ds}(V_{gs}, V_{d}) \) at a saturated channel condition as follows: all higher terms in \( \psi \) are assumed to be zero, \( \lambda \) is determined from the slope of the \( I_{ds}-V_{ds} \) characteristic, \( I_{pk} \) and \( V_{pk} \) are determined at the peak transconductance \( g_{mpk} \). The intrinsic maximum transconductance \( g_{mpk} \) is calculated from the measured maximum transconductance \( g_{mpkborn} \) by taking into account the feedback effect due to the source resistance, \( R_s \), which can be obtained from dc-measurement [7]:

\( g_{mpk} = \frac{g_{mpkborn}}{(1 - R_s g_{mpkborn})} \) (4)
$P_1$ is now obtained as

$$ P_1 = \frac{g_{mpk}}{I_{pk}(1 + \lambda V_d)} \approx \frac{g_{mpk}}{I_{pk}}. \quad (5) $$

In some HEMTs, $V_{pk}$ is weakly dependent on the drain voltage $V_{ds}$ in the saturated region. This effect can be accounted for by

$$ V_{pk} = V_{pko} + \gamma \cdot V_{ds}. \quad (6) $$

In the non-saturated region and for negative $V_{ds}$, $V_{pk}$ will vary considerably with $V_{ds}$, as will be discussed later. The dependence of $V_{pk}$ on $V_{ds}$ must be found (experimentally or modeled) and the model will predict the transistor performance correctly.

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

$$ C(V_{gs}, V_{ds}) = C_A \left[ \tanh \left( V_{gs} \right) \right] C_B \left[ \tanh \left( V_{ds} \right) \right] \quad (7) $$

as suggested in [8], [9]. Due to the similarity of $I_{gs} [V_{gs}, V_{ds}]$ and $C_{gs} [V_{gs}, V_{ds}]$ the functions can be expressed as

$$ C_{gs} = C_{gs0} \left[ 1 + \tanh \left( \psi_1 \right) \right] \left[ 1 + \tanh \left( \psi_2 \right) \right] \quad (8) $$

$$ C_{gd} = C_{gd0} \left[ 1 + \tanh \left( \psi_3 \right) \right] \left[ 1 - \tanh \left( \psi_4 \right) \right] \quad (9) $$

where

$$ \psi_1 = P_{0gs} + P_{1gs} V_{gs} + P_{2gs} V_{gs}^2 + P_{3gs} V_{gs}^3 + \cdots $$

$$ \psi_2 = P_{0gd} + P_{1gd} V_{ds} + P_{2gd} V_{ds}^2 + P_{3gd} V_{ds}^3 + \cdots $$

$$ \psi_3 = P_{0gd} + P_{1gd} V_{gs} + P_{2gd} V_{gs}^2 + P_{3gd} V_{gs}^3 + \cdots $$

$$ \psi_4 = P_{0gd} + (P_{1gd} + P_{1cc} V_{gs}) V_{ds} + P_{2gd} V_{ds}^2 + P_{3gd} V_{ds}^3 + \cdots $$

The term $P_{1cc} V_{gs} V_{ds}$ reflects the cross-coupling of $V_{gs}$ and $V_{gd}$ on $C_{gd}$. When an accuracy on the order of 5–10% of $C_{gs}$ and $C_{gd}$ is sufficient (8)–(13) can be simplified to:

$$ C_{gs} = C_{gs0} \left[ 1 + \tanh \left( P_{1gs} V_{gs} \right) \right] \left[ 1 + \tanh \left( P_{1gd} V_{ds} \right) \right] \quad (14) $$

$$ C_{gd} = C_{gd0} \left[ 1 + \tanh \left( P_{1gd} V_{gs} \right) \right] \left[ 1 - \tanh \left( P_{1gd} V_{ds} \right) \right]. \quad (15) $$

Equation (15) can be further simplified if cross-coupling at large drain voltages ($V_{ds} > 1$ V) is neglected:

$$ C_{gd} = C_{gd0} \left[ 1 + \tanh \left( P_{1gd} V_{gs} \right) \right] \left[ 1 - \tanh \left( P_{1gd} V_{ds} \right) \right]. \quad (16) $$

These equations (14)–(16) are suitable for $\delta$-doped HEMTs with an undoped AlGaAs spacer-layer, as investigated in this study, since they have a saturated $C_{gs} [V_{gs}]$ characteristic for increasing $V_{gs}$ due to the 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 a commercially available MESFET and different submicron gate-length devices, including different $\delta$-doped pseudomorphic HEMTs on GaAs and lattice matched to InP (Fig. 1), with mushroom gates of length from 0.15 mm to 0.35 mm and gate width from 50 mm to 200 mm, fabricated in our laboratory at Chalmers University. $f_T$ and $f_{max}$ were 70–110 GHz and 120–200 GHz respectively for the short gate-length devices.

DC-parameters were measured by using a HP 4145B parameter analyser. In Figs. 2–5, the result of the measured ($V_{ds} = 2$ V) and modeled dc parameters of the different transistors is shown. For most devices, the function $\psi$, extracted from the measured drain current $I_{ds}$, is almost a straight line and it is possible to use only the first term in $\psi$ to model the transistor (Figs. 2, 3, 4). For some of them (Fig. 5) it is necessary to use more terms to improve the fitting.

In Fig. 6(a), the measured variation of $V_{pk}$ for one transistor (PM3) with a gate width, $L_w$, of $2 \times 25$ mm is shown. At low and at negative values of $V_{ds}$, $V_{pk}$ varies strongly with $V_{ds}$. Therefore, the $V_{pk}$ dependence also has to be modeled if the operating conditions of the device correspond to these cases. In the same figure, the modeled $V_{pk}$ is plotted using different approximating functions for the $V_{pk}$ dependence. In Figs. 6(b) and (c), the measured and modeled $I_{ds}$ and $g_{ms}$ versus $V_{gs}$, are presented.

The $S$-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. Here we present results of measurements of the HEMT (PM2) with the gate width of 200 mm and gate length 0.35 mm for which the influence of fringing and pad capacitances is of less importance compared to the short gate length devices. $S$-parameters were measured at the following bias points for parameter extraction: $V_{ds} = -1$ V, $-0.5$ V, 0 V, 0.75 V, 2 V, 3 V and $V_{gs} = -1.5$ V to +0.5 V with a step of 0.25 V. The parasitic parameters of the transistor (Fig. 7(a)) can be found most accurately at $V_{ds} = 0$. This regime is also important for mixers working in the resistive mode [10]. At $V_{ds} = 0.75$ V, $V_{ds}$ is saturated. At $V_{ds} = 2–3$ V the transistor is working in its normal operating mode.

The intrinsic parameters of the equivalent circuit (Fig. 7(a)) were derived. The parasitic parameters $L_g$, $L_d$, $R_g$, $R_d$, $C_p$ were fixed at the parameter values extracted from the $S$-parameter measurement at $V_{ds} = 0$.

Our model was easily implemented in a commercial Harmonic Balance-simulator (MDS from HP) as a custom defined equation model. The model parameters of the PM2 ($L_w = 200$ mm, $L_g = 0.35$ mm) HEMT are listed in Table I. For this particular HEMT we have to include the cubic
HEMT

500 Å GaAs (\(N_d=2\times10^{18}\))
400 Å Al\(\text{0.24} \) Ga\(\text{0.76} \) As (1.5\(\times10^{18}\))
20 Å Al\(\text{0.24} \) Ga\(\text{0.76} \) As (undoped)
5000 Å GaAs (undoped) < 1.1\(\times10^{14} \) \(\text{cm}^{-3}\)
Semi-insulating GaAs 650 \(\mu\)m

(b)

Pseudomorphic HEMT (PM2)

400 Å GaAs (\(N_d=3\times10^{18}\))
250 Å Al\(\text{0.25} \) Ga\(\text{0.75} \) As (undoped)
40 Å Al\(\text{0.25} \) Ga\(\text{0.75} \) As (undoped)
150 Å In\(\text{0.2} \) Ga\(\text{0.8} \) As (undoped)
1 \(\mu\)m GaAs (undoped)
400 Å GaAs/AlGaAs S-L
Semi-insulating GaAs

(d)

Double \(\delta\)-doped HEMT (PM3)

300 Å GaAs (\(N_d=4\times10^{18}\))
500 Å Al\(\text{0.25} \) Ga\(\text{0.75} \) As (undoped)
25 Å Al\(\text{0.25} \) Ga\(\text{0.75} \) As (undoped)
120 Å In\(\text{0.2} \) Ga\(\text{0.8} \) As (undoped)
50 Å GaAs < 1.1\(\times10^{14} \) \(\text{cm}^{-3}\)
5000 Å GaAs (undoped)
10e(20Å+20Å) AlAs/GaAs (1.1015)
Semi-insulating GaAs 650 \(\mu\)m

(c)

Fig. 1. Structure of the devices. (a) Ordinary HEMT. (b) Pseudomorphic HEMT (PM2). (c) Double \(\delta\)-doped pseudomorphic HEMT (PM3). (d) Lattice matched to InP HEMT.

Fig. 2. Measured \(V_d = 2 \) V (dots) and modeled (solid lines) characteristic of ordinary HEMT (\(L_w = 2 \times 100 \) \(\mu\)m, \(L_s = 0.15 \mu\)m). (a) Drain current \(I_d\), versus gate voltage, \(V_g\) (\(I_d = 31 \) mA, \(\lambda = 0.02\), \(\alpha = 1.3\), \(V_g = 0.51\) V). (b) \(\psi\)-function versus gate voltage, \(V_g\) (\(P_1 = 1.8\), \(P_2 = 0\), \(P_3 = -0.09\)). (c) Transconductance, \(g_{m}\), versus gate voltage, \(V_g\). (d) Derivative of the transconductance \(d(g_m)/dV_g)\).
Fig. 3. Measured $V_d = 2$ V (dots) and modeled (solid lines) characteristics of pseudomorphic HEMT (PM2) ($L_g = 2 \times 100 \mu m$, $L_d = 0.15 \mu m$). (a) Drain current, $I_{ds}$, versus gate voltage, $V_g$, ($I_{pk} = 38$ mA, $\lambda = 0.02$, $\alpha = 1.5$, $V_{pk} = 0.12$ V). (b) $\psi$-function versus gate voltage, $V_g$, ($P_1 = 1.9$, $P_2 = 0$, $P_3 = 0.83$). (c) Transconductance, $g_m$, versus gate voltage, $V_g$. (d) Derivative of the transconductance $d(g_m)/dV_g$.

Fig. 4. Measured $V_d = 2$ V (dots) and modeled (solid lines) characteristics of double $\delta$-doped HEMT (PM3) ($L_g = 2 \times 100 \mu m$, $L_d = 0.15 \mu m$). (a) Drain current, $I_{ds}$, versus gate voltage, $V_g$, ($I_{pk} = 69$ mA, $\lambda = 0.025$, $\alpha = 1.3$, $V_{pk} = -0.025$ V). (b) $\psi$-function versus gate voltage ($P_1 = 1.42$, $P_2 = 0$, $P_3 = -0.02$). (c) Transconductance, $g_m$, versus gate voltage, $V_g$. (d) Derivative of the transconductance $d(g_m)/dV_g$. 

$\psi$-function, $V_g$, ($P_1 = 1.9$, $P_2 = 0$, $P_3 = 0.83$).
In Fig. 5, measured $V_d = 2$ V (dots) and modeled (solid lines) characteristics of InP-HEMT ($L_w = 2 \times 50 \mu m$, $L_g = 0.15 \mu m$). (a) Drain current, $I_{ds}$, versus gate voltage, $V_g$, ($I_{ds} = 15$ mA, $\lambda = 0.02$, $\alpha = 1.5$, $V_{ds} = 0.02$ V). (b) $\psi$-function versus gate voltage, $V_g$ ($P_1 = 2.4$, $P_2 = -0.4$, $P_3 = 0.02$ V). (c) Transconductance, $g_m$, versus gate voltage, $V_g$. (d) Derivative of the transconductance $d(g_m)/dV_g$.

In Fig. 6, measured (dots) and modeled (solid lines) characteristics of double $\delta$-doped HEMT (PM3) ($L_w = 2 \times 25 \mu m$, $L_g = 0.15 \mu m$). (a) $V_{ds}$ versus $V_g$: 1) $V_{ds} = -0.27 + 0.65 \tanh (V_g - 0.34)$ and 2) $V_{ds} = -0.1 + 0.5 V_g - 0.13 V_g^3$. (b) Drain current, $I_{ds}$, versus gate voltage, $V_g$, ($I_{ds} = 16$ mA, $\lambda = 0.05$, $\alpha = 1.3$, $P_1 = 1.65$, $P_2 = 0$, $P_3 = 0.5$, $F_1 = -0.27 + 0.65 \tanh (V_g + 0.34)$). (c) Transconductance, $g_m$, versus gate voltage, $V_g$.

In order to improve the fitting of the drain current and its derivatives at voltages close to pinch-off, all terms except $P_1$ and $P_3$ are zero.

In Fig. 7(b)–(d), the measured and modeled $I_{ds}$–$V_{ds}$ characteristics, the transconductance $g_m$, and the output resistance, $R_{ds}$, are plotted, respectively.

Fig. 8 shows the measured and simulated $S$-parameters of the transistor at different bias points. The difference between the modeled and simulated values is small for all $S$-parameters. The model has been also used to simulate the performance of different non-linear circuits like mixers and multipliers with good accuracy [12], [13].
Figs. 9(a)–(c) show the measured and modeled dependencies of $C_{gs}$ and $C_{gd}$ for transistors with gate dimensions of 200 $\mu$m $\times$ 0.35 $\mu$m. The commonly used models (pn-junction or Statz models) are not appropriate for this case. For the studied pulse-doped pseudomorphic HEMT the following simple expressions were found (with simple curve fitting procedure [11]) giving an accuracy, which is sufficient for most practical cases:

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

$$\cdot \left[ 1 + \tanh \left( 0.4V_{ds} \right) \right]$$

(17)

**TABLE I**

<table>
<thead>
<tr>
<th>$R_s$ $\Omega$</th>
<th>$R_g$ $\Omega$</th>
<th>$R_d$ $\Omega$</th>
<th>$C_{ds}$ $\mu F$</th>
<th>$C_{gs}$ $\mu F$</th>
<th>$C_{gd}$ $\mu F$</th>
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$I_{pk}$ [mA] $P_1$ $P_3$ $V_{pk}$ [V] $\lambda$ $\alpha$

| 26.3 | 3.35 | 7 | 0.55 | 0.02 | 3 |

Fig. 8. The measured (dots) and modeled (solid lines) $S$-parameters of the PM2 HEMT ($L_g = 200 \mu$m, $L_d = 0.35 \mu$m) for $V_{gs} = 2$ V and $V_{ds} = 0$ V, 0.1 V and 0.45 V. (a) Magnitude of $S_{21}$. (b) $S_{21}$. (c) $S_{11}$. (d) $S_{22}$. 

Fig. 7. Measured (dots) and modeled (solid lines) PM2 HEMT characteristics ($L_w = 200 \mu$m, $L_g = 0.35 \mu$m). (a) The equivalent circuit of the transistor. (b) Drain current, $I_{ds}$, versus drain voltage, $V_{ds}$. (c) Drain current, $I_{ds}$, and transconductance, $g_m$, versus gate voltage, $V_{gs}$. (d) Drain-source resistance, $R_{ds}$, gate voltage, $V_{gs}$. 

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**TABLE I**

| Extracted Parameters of the HEMT |
|---|---|---|---|---|---|
| $R_s$ $\Omega$ | $R_g$ $\Omega$ | $R_d$ $\Omega$ | $C_{ds}$ $\mu F$ | $C_{gs}$ $\mu F$ | $C_{gd}$ $\mu F$ |
| 3 | 3.5 | 3 | 6 | 60 | 0.28 | 35 |

$I_{pk}$ [mA] $P_1$ $P_3$ $V_{pk}$ [V] $\lambda$ $\alpha$

| 26.3 | 3.35 | 7 | 0.55 | 0.02 | 3 |
\[ C_{gd} = C_{gdo} \left[ 1 + \tanh (0.48 V_{gs}) \right] \]
\[ \cdot \left[ 1 - \tanh (0.55 V_{ds} - 0.048 V_{ds}^2 + 0.2 V_{gs} V_{ds}) \right] \]
\[ (18) \]

and for the simplified equation of \( C_{gd} \) we obtain:
\[ C_{gd} = C_{gdo} \left[ 1 + \tanh (0.48 V_{gs}) \right] \left[ 1 - \tanh (0.55 V_{ds}) \right] \]
\[ (19) \]

where \( C_{gdo} = C_{gdo} = 145 \text{ fF} \) are the capacitances for \( V_{gs} = V_{ds} = 0 \).

In Fig. 9(b) and (c), the modeled \( C_{gd} \) using (18) and (19) are shown. Evidently even such a simple equation as (19) gives good accuracy. When higher accuracy is required more terms should be included.

Fig. 9. Measured (dots) and modeled (solid lines) capacitances of the PM2 HEMT \((L_w = 200 \mu\text{m}, L_g = 0.35 \mu\text{m})\): \( C_{gs} = C_{gdo} = 145 \text{ fF} \). (a) \( C_{gs} \) versus \( V_{ds} \), eq. (17). (b) \( C_{gd} \) versus \( V_{ds} \), eq. (18). (c) \( C_{gd} \) versus \( V_{ds} \), eq. (19).

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In Fig. 9(b) and (c), the modeled \( C_{gd} \) using (18) and (19) are shown. Evidently even such a simple equation as (19) gives good accuracy. When higher accuracy is required more terms should be included.
The same study was performed on an ordinary MESFET and the model was shown to work equally well for this kind of device. Model parameters were extracted for packaged MESFETs fabricated by different manufacturers. DC- and S-parameters were measured using a Maury MT-950 transistor fixture and Wiltron 360/HP 8510 C ANA in the frequency range 0.1–18 GHz.

The measured and simulated dc parameters of the Mitsubishi MGF 1303, the drain current, $I_{ds}$, the $V$-function, the transconductance, $g_m$, the derivative of the transconductance, $g_m$, are shown in Fig. 10. We have used a more complicated equivalent circuit of the transistor (Fig. 11(a)) to model the packaged transistors accurately. Parameters were extracted in the same way as for the HEMT as described above. The model parameters listed in Table II extracted for a MESFET (MGF 1303), were used in Harmonic Balance Simulator (MDS) to simulate the dc and microwave performance of this transistor.

In Fig. 11(b)–(d) the measured and modeled $I_{ds}$–$V_{ds}$ dependence, the transconductance, $g_m$, versus gate voltage $V_{gs}$, the output resistance, $R_{ds}$, for this packaged transistor are shown. Measured and simulated S-parameters for the MESFET at different bias conditions are shown in Fig. 12. The difference between measured and modeled $I_{ds}$ versus $V_{gs}$, $g_m$ and $S_{21}$ is less than 5%.

**Conclusions**

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

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