A New Emipirical *I–V* Model for HEMT Devices

Y. C. Chen, *Member, IEEE,* D. L. Ingram, H. C. Yen, *Member, IEEE,* R. Lai, and D. C. Streit, *Senior Member, IEEE*

***Abstract*—We have developed a new empirical model to represent the current–voltage (I–V) characteristics of HEMT devices. This model is simple and yet capable of representing the HEMT I–V characteristics with high accuracy. Excellent modeling of the measured drain current, its first (transconductance), second, and third derivatives with respect to gate voltage for multiple drain biases is demonstrated. A simple model extraction procedure has been developed and is described in the letter.**

I. Introduction

ACCURATE HEMT *I–V* models are required for the design and simulation of nonlinear circuits based on these devices. Different applications demand different degrees of accuracy on the model. For example, in power amplifier design, the *I–V* model must be capable of accurately representing $I_{\rm ds}$ and g_m characteristics in order to predict the output power and power-added efficiency. On the other hand, to simulate the third-order intermodulation, the third- and higher order derivatives of $I_{\rm ds}$ (second- and higher order derivatives of g_m) with respect to $V_{\rm gs}$ must be modeled accurately. The importance of modeling the derivatives of *I–V* characteristics has been pointed out previously by Maas *et al.* [1]. Other equivalent circuit element parameters such as $C_{\rm gs}$, $C_{\rm dg}$, and $C_{\rm ds}$ also exhibit strong nonlinearity and need to be represented accurately.

Different empirical models have been proposed to represent the *I–V* characteristics of MESFET and HEMT's. Equation-based models developed by Curtice *et al.* [2] and Angelov *et al.* [3], [4], in principle, can model the high-order derivatives of $I_{\rm ds}$ with respect $V_{\rm gs}$. However, good accuracy can be achieved only for a certain $V_{\rm ds}$. Maas's model [1] is capable of representing high-order derivatives of $I_{\rm ds}$ with respect $V_{\rm gs}$ for multiple drain biases. However, it requires many terms and a special extraction techniques. A measurement-based model developed by Root *et al.* [5] is accurate and versatile. However, the model and its parameter extraction package are available only commercially.

We propose an equation-based empirical *I–V* model for HEMT's and MESFET's. This model is capable of representing $I_{\rm ds}$ and its derivatives up to the third for multiple drain biases. Model Parameters can be easily extracted by performing spreadsheet-based curve fittings to the measured *I–V* data.

Manuscript received May 11, 1998.

The authors are with TRW Electronics & Technology Division, Redondo Beach, CA 90278 USA.

Publisher Item Identifier S 1051-8207(98)08925-9.

II. The *I–V* Model

The drain current is expressed as

$$I_{\rm ds}(V_{\rm gs}, V_{\rm ds}) = \left(I_{\rm max}^{-1} + I_{\rm dso}^{-1}\right)^{-1} \tag{1}$$

where $I_{\rm max}$ is the maximum channel current and is a function of $V_{\rm ds}$ only, and $I_{\rm dso}$ is a function of both $V_{\rm ds}$ and $V_{\rm gs}$. When $V_{\rm ds}$ is biased to near pinch-off, $I_{\rm dso}$ is much smaller than $I_{\rm max}$ and $I_{\rm ds}$ approximately equals $I_{\rm dso}$. On the other hand, when $V_{\rm gs}$ is biased to fully opening the channel, $I_{\rm dso}$ becomes much greater than $I_{\rm max}$, and $I_{\rm ds}$ approaches $I_{\rm max}$. The function $I_{\rm max}$ has a $V_{\rm ds}$ dependence same as that in [2]–[4] and [6], and is expressed as follows:

$$I_{\rm max}(V_{\rm ds}) = {\rm IPK} \times \tanh(V_{\rm ds}/{\rm VK}) \times (1 + {\rm LAM} \times V_{\rm ds}). \tag{2}$$

$I_{\rm dso}$ is an exponential function of $V_{\rm ds}$ and $V_{\rm gs}$ and is expressed as

$$I_{\rm dso} = \exp(\psi) \tag{3}$$

where

$$\psi(V_{\rm gs}, V_{\rm ds}) = \sum_{i=0\,{\rm to}\,m} a_i \times V_{\rm gs}^i, \quad m = 4 \tag{4}$$

$$a_i(V_{\rm ds}) = \sum_{j=0\,{\rm to}\,n} a_{ij} \times V_{\rm ds}^j, \quad n = 2. \tag{5}$$

Equation (4) allows the high-order derivatives of $I_{\rm ds}$ with respect to $V_{\rm gs}$ to be modeled accurately and (5) enables the same accuracy for multiple drain biases. This model exhibits well-behaved pinchoff characteristics and well-bounded maximum channel current. The equations are continuous for all order of derivatives. Most importantly, the model satisfies the current conservation requirement [5]

$$\frac{\partial^2 I_{\rm ds}}{\partial V_{\rm ds}\partial V_{\rm gs}} = \frac{\partial^2 I_{\rm ds}}{\partial V_{\rm gs}\partial V_{\rm ds}} \tag{6}$$

which is required for the harmonic balanced simulation to converge at large-signal levels.

III. Model Extraction and Verification

Model parameters—IPK, VK, LAM, and a_{ij}'s—can be easily extracted by performing spreadsheet-based curve fittings to the measured data. The fitting procedure is described as followed. First, set IPK to twice of the drain current where the peak g_m occurs, VK to 65% of the knee voltage, and LAM to the slope of measured $I_{\rm max}$. Next, calculate $\psi(V_{\rm gs}, V_{\rm ds})$ using (1)–(3). Then, perform polynomial curve fitting to the $\psi(V_{\rm gs})$ to extract a_i at multiple $V_{\rm ds}$ values. The a_{ij}'s can

TABLE I
I–V MODEL PARAMETERS EXTRACTED FOR A 0.1-μm T-GATE GaAs HEMT WITH 40-μm TOTAL GATE PERIPHERY

IPK	VK	LAM	a_{00}	a_{01}	a_{02}
0.0324	0.496	0.0145	-3.695	0.098	-0.0008
a_{10}	a_{11}	a_{12}	a_{20}	a_{21}	a_{22}
3.83	-0.202	0.008	-2.72	1.4	-0.174
a_{30}	a_{31}	a_{32}	a_{40}	a_{41}	a_{42}
4.54	-1.49	0.12	0.84	-1.96	0.31

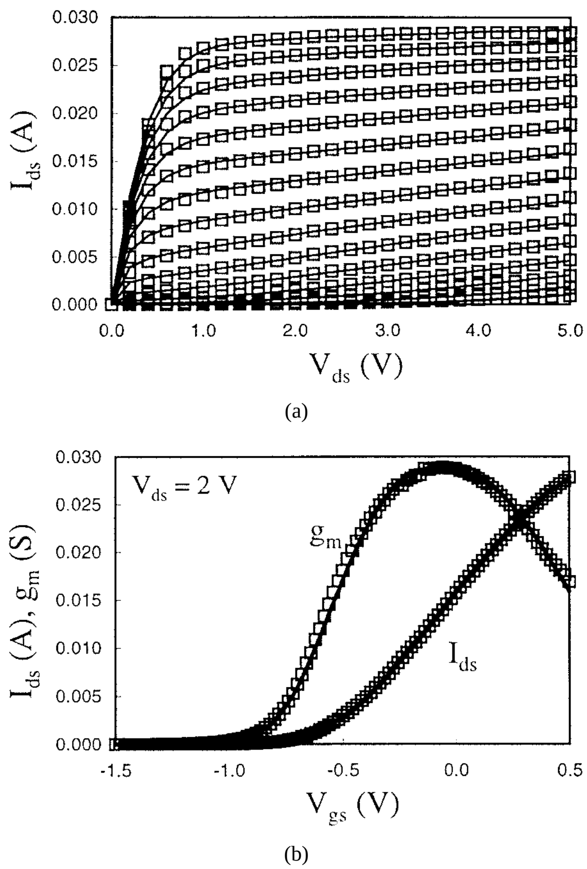

Fig. 1. The measured (square symbols) and modeled (solid curves) dc *I–V* (a) and g_m (b) characteristics for a 0.1-μm T-gate GaAs HEMT with 40-μm total gate periphery.

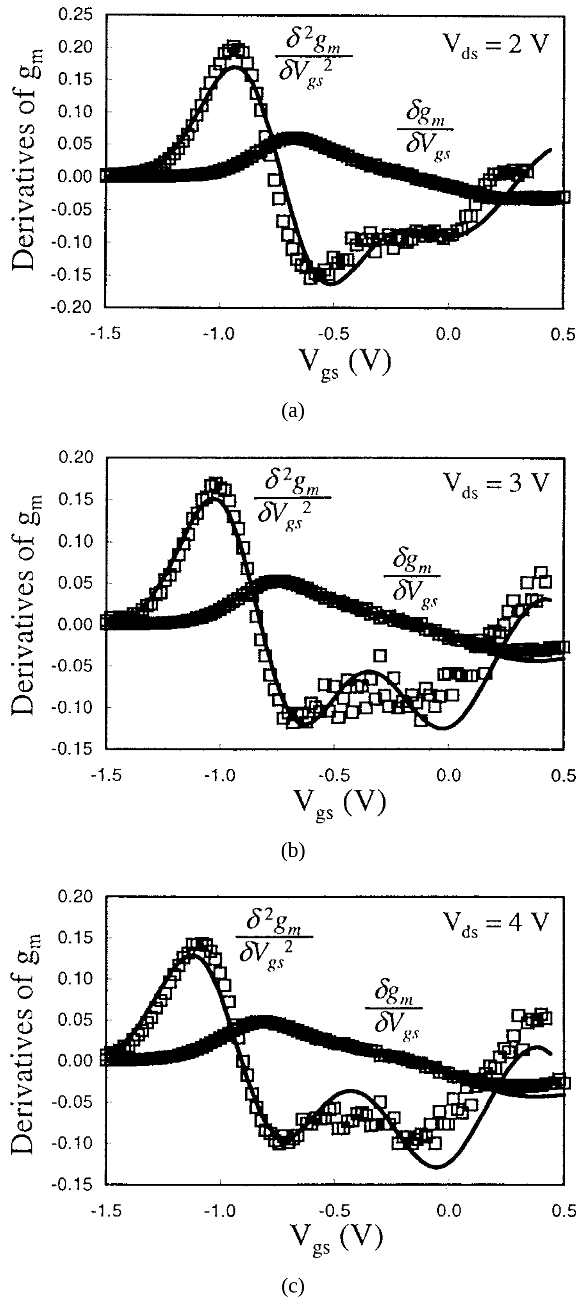

Fig. 2. The measured (square symbols) and modeled (solid curves) g_m first and second derivatives for a 0.1-μm T-gate GaAs HEMT with 40-μm total gate periphery biased at (a) $V_{\rm ds} = 2$ V, (b) $V_{\rm ds} = 3$ V, and (c) $V_{\rm ds} = 4$ V.

then be extracted by performing curve fittings to the $a_i(V_{\rm ds})$. Excellent fitting to *I–V* and g_m can be obtained at this stage. Final optimization is necessary to accurately model the second derivative of g_m. Usually adequate accuracy can be achieved with $m = 4$ and $n = 2$. Better accuracy can be achieved by increasing m and n without complicating the parameter extraction.

Model parameters have been extracted for various GaAs and InP-based HEMT devices. The data reported here were measured from a 0.1-μm T-gate GaAs HEMT device fabricated using TRW's 2-mil GaAs HEMT MMIC production process [7]. Double-doped GaAs pseudomorphic HEMT structure with a $In_{0.2}Ga_{0.8}As$ channel sandwiched between $Al_{0.25}Ga_{0.75}As$ layers was used. Typical g_m and $I_{\max}$ measured from standard test devices at $V_{\rm ds} = 2$ V are 720 mS/mm and 750 mA/mm, respectively. The dc data were measured using HP4145A parameter analyzer. The higher order derivatives of drain currents were obtained by differentiating the *I–V* data with fine $V_{\rm gs}$ steps.

Shown in Table I is the model extracted for a 0.1-μm T-gate GaAs HEMT with 40-μm total gate periphery. The measured (square symbols) and modeled (solid curves) dc *I–V* and g_m characteristics for this device are shown in Fig. 1, and the first and second derivatives of g_m are shown in Fig. 2. Note that good match between measurements and the model was achieved up to the second derivative of g_m at multiple drain biases. This is the first demonstration of an equation-based HEMT model capable of representing HEMT *I–V* characteristics with this degree of accuracy.

IV. Conclusion

We have developed an empirical *I–V* model capable of representing HEMT *I–V* characteristics accurate up to the second derivative of g_m at multiple drain biases. The model is very simple and practical and can be easily implemented as user defined function for microwave circuit simulator such as Libra. Model parameter extraction is straightforward and can be done by spreadsheet-based calculations.

References

[1] S. Maas and D. Neilson, "Modeling of MESFET's for intermodulation analysis of mixers and amplifiers," in *1990 IEEE MTT-S Microwave Symp. Dig.*, pp. 1291–1294.

[2] W. Curtice and M. Ettenberg, "A nonlinear GaAs FET model for use in the design of output circuits for power amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 2, p. 1383, 1985.

[3] I. Angelov, H. Zirath, and N. Rorsman, "A new empirical model for HEMT and MESFET devices," *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 12, pp. 2258–2266, 1992.

[4] I. Angelov, H. Zirath, and N. Rorsman, "Validation of a nonlinear transitor model by power spectrum characteristics of HEMT's and MESFET's," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 1046–1051, May 1995.

[5] D. Root and B. Hughes, "Principles of nonlinear active device modeling for circuit simulation," presented at 32nd Automatic Radio Frequency Techniques Group Conf., Dec. 1988.

[6] H. Staz, P. Newman *et al.*, "GaAs FET device and circuit simulation in SPICE," *IEEE Trans. Electron Devices*, vol. ED-34, no. 2, pp. 160–166, 1987.

[7] M. Biedenbender, R. Lai, J. Lee, S. Chen, K. L. tan, P. H. Liu, A. Freudenthal, D. C. Streit, B. Allen, and H. wang, "A 0.1 μm W-band HEMT production process for high yield and high performance low noise and power MMIC's," in *16th Annu. IEEE GaAs IC Symp. Dig.*, Philadelphia, PA, 1994, pp. 325–328.

[8] P. Huang, E. Lin, R. Lai, M. Biedenbender, T. W. Huang, H. Wang, C. Geiger, T. Block, and P. H. Liu, "A 94 GHz monolithic high output power amplifier," in *1997 IEEE MTT-S Microwave Symp. Dig.*, pp. 1175–1178.