A complete self-defined empirical model for enhancement-mode AlGaAs/InGaAs pHEMTs

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Abstract – **We propose a complete self-defined empirical large–signal and noise included model for the enhancement -mode AlGaAs/InGaAs pHEMTs. This model achieves the excellent fitting of the dc transconductance, g_m, which considers the difference of the drain-to-source conductance between dc and rf measurement. In addition, for a full perdition at various biases, all parameters of the model are characterized versus the voltages of gate-to-source and drain-to-source. In consequence, the predictions of the power and IM3 are considerable good. Additionally it can also predict the NF_{min} and Γ_{opt} points well using the noise parameters by calculating the thermal noise of the equivalent circuit model. This noise figure prediction included model is not always available from the mostly used conventional pHEMT models.**

I. INTRODUCTION

In order to increase the accuracy of the MMIC design, a complete and accurate active device model is the key component for the circuit designer. But the traditional used models such as Curtice- cubic model [1] and Statz model [2], the fitting parameters of the device current-voltage are obtained mainly from the $I_{ds}(V_{gs},V_{ds})$ curves. Although they provide a reasonable agreement with the measurement results, but for the g_m curve fitting is certainly not accurate enough, which is more serious on these advanced FETs, such as pHEMT, doped-Channel HFET, mHEMT, and InP HEMT. Mass [3] and Angelov [4] pointed out that not only the device I–V characteristics but also their derivatives have to be modeled correctly. Based on this principle, the EE_HEMT1 model [5] with the derivative formulation is implemented in the ADS^{TM}. However, the expressions in EE_HEMT1 model are too complicated, and the numbers of the fitting parameters in the expression are much more than the conventional models. Therefore in order to extract the parameters of EE_HEMT1 model we need the help from the Agilent IC-CAP software especially. Hence, we propose a new simple self-defined current–voltage equation, where the fitting parameters are extracted directly from device transconductance (g_m) and dc I–V characteristics. The fitting equations and parameters can be easily defined in the simulation tool based on your particular interest, which provide a great flexibility of device modeling. Additionally the pHEMT devices have not only good power performance [6] but also excellent noise behavior [7]. Therefore we also add the noise parameters P, R and C in our so called self-defined model to predict the minimum noise figure, NF_{min} and the Γ opt points by considering the thermal noise of small-signal model. This model has been applied to the enhancement-mode pHEMTs (E-pHEMTs) in this study. E-pHEMTs have provided very promising characteristics, rf power performance and noise performance, which are very attractive to the handset power amplifier applications. This report presents this proposed complete self-defined model including power and noise characteristics, which can precisely predict the microwave gain distortions, large-signal characteristics, the third order inter modulation (IM3) and NF_{min} of E-pHEMTs.

II. DETAILED DESCRIPTIONS OF THE LARGE-SIGNAL MODEL

The equivalent circuit topology of our large-signal model is shown in Fig. 1. The proposed model contains a new formulation of drain current (I_{ds}), gate-to-source capacitance (C_{gs}), gate-to-drain capacitance (C_{gd}), channel resistance (R_i), drain-to-source resistance (R_{ds_rf} and R_{ds_dc}) and the two diodes, *diode*$_{\_gd}$ and *diode*$_{\_gs}$ which provide the dc diode current based on the measured characteristics of the E-pHEMTs. The tested device with a gate-length of 0.8 μm demonstrates a peak g_m of 350 mS/mm, an f_t of 23 GHz, and an f_{max} of 70 GHz.

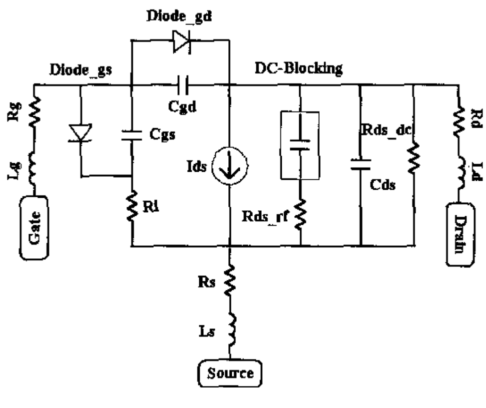

Fig. 1 The equivalent circuit of the AlGaAs/InGaAs pHEMTs.

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In order to realize our model in the RF circuit simulation, we used the Symbolic Defined Device (SDD) program of the ADS™ to construct our model. The SDD provides an easy and flexible way to connect each node of the equivalent circuit model and the fitting equations between two nodes. Because of using it to establish the modified equivalent circuit and define all parameters by new empirical descriptions by ourselves. Therefore all the small-signal parameters definitions are extracted at various bias points after using the Yang-Long, Cold-FET measurement and matrix transform at 5 GHz. As compared with the third-order polynomial current equation of the Curtice model, the current equation of this model is a user-defined polynomial equation versus the intrinsic gate-to-source bias, V_{gs}, which can predict the transconductance, g_m, versus V_{gs} from -0.5 V to 1.3 V correctly. Additionally, the current equation also includes the dc output resistance (R_{ds_dc}) measured from the dc I-V curves. To predict the output conductance at the high frequencies, we added a dc-blocking and a series rf output resistance (R_{ds_rf}) instead of the traditional C_{rf} and R_{rf} parameters of the Curtice model, where the extractions of the R_{ds_dc} and R_{ds_rf} become clear. The total output conductance of the rf measurement is therefore R_{ds_dc} paralleling with R_{ds_rf}, and the total output conductance is only G_{ds_dc}. Consequently we can predict the S_{22} and I-V curves precisely and simultaneously.

As to our drain current model, we started from the parameter fitting of the g_m-V_{gs} curves at the V_{ds} = 3V, and the integration form was subsequently used to obtain the I_{ds}-V_{gs} curves [8]. The current equation for E-pHEMT is expressed as

$$g_m = A_0 + A_1 \cdot V_{gsi} + A_2 \cdot V_{gsi}^2 + A_3 \cdot V_{gsi}^3 + A_4 \cdot V_{gsi}^4 + A_5 \cdot V_{gsi}^5 + A_6 \cdot V_{gsi}^6 \quad (1)$$

$$R_{ds\_dc} = B_0 + B_1 \cdot V_{gsi} + B_2 \cdot V_{gsi}^2 + B_3 \cdot V_{gsi}^3 \quad (2)$$

$$I_{ds} = \left(\int g_m dV_{gsi} + I_{dss}\right) \cdot \tan(\alpha \cdot V_{dsi}) + V_{dsi} / R_{ds\_dc} \quad (3)$$

$$\alpha = C_0 + C_1 \cdot V_{gsi} + C_2 \cdot V_{gsi}^2 + C_3 \cdot V_{gsi}^3 \quad (4)$$

V_{dsi} and V_{gsi} are the intrinsic gate-to-source and gate-to-drain voltages. I_{dss} is the drain current at V_{gsi} = 0V and V_{ds} = 3V. A_i, B_i, and C_i are the fitting parameters for device operating at the saturation region (V_{ds} = 3V). The measured and simulated results are shown in Fig. 2 for a 200μm wide E-pHEMT, where an excellent agreement can be reached for the I_{ds}-V_{ds} and g_m-V_{gs} curves simultaneously, up to V_{gs} = 1.3V. In addition to the nonlinear g_m description, the other important nonlinear parameters shown in Fig. 1, such as C_{gs}, C_{gd}, and R_{ds} are also included in our large-signal model. After Cold FET and Yang-Long measurements, we can obtain all these parameters at different biases. The following equations are chosen to model these nonlinear characteristics of C_{gs}, C_{gd}, and R_{ds_rf} versus V_{gsi} and V_{dsi}, where D_{ij}, E_{ij}, and F_{ij} are the fitting parameters for the device. This large-signal model is capable of producing accurate S parameters at arbitrary dc bias points of the E-pHEMT. Fig. 3 shows the measured (lines) and modeled (dots) S parameters of the E-pHEMT at different bias points (V_{ds} = 3V, V_{gs}=0.3, 0.1, 0V). The differences between measured and modeled values are limited through the frequency range from 50 MHz to 20.05 GHz

$$C_{gs} = (D_{01} + D_{02} \cdot V_{dsi}) + (D_{11} + D_{12} \cdot V_{dsi}) \cdot V_{gsi} + (D_{21} + D_{22} \cdot V_{dsi}) \cdot V_{gsi}^2 + (D_{31} + D_{32} \cdot V_{dsi}) \cdot V_{gsi}^3 + (D_{41} + D_{42} \cdot V_{dsi}) \cdot V_{gsi}4 \quad (5)$$

$$C_{gd} = E_{00} + \left(1 + \tanh\left(E_{10} + E_{11} \cdot V_{gsi} + E_{12} \cdot V_{gsi}^2 + E_{13} \cdot V_{gsi}^3\right)\right) \quad (6)$$

$$R_{ds} = R_{ds\_rf} // R_{ds\_dc} = \left(F_{00} + F_{01} \cdot V_{dsi} + F_{02} \cdot V_{dsi}^2 + F_{03} \cdot V_{dsi}^3\right) + (F_{11}) \cdot \exp\left(-V_{gsi} / F_{12}\right) \quad (7)$$

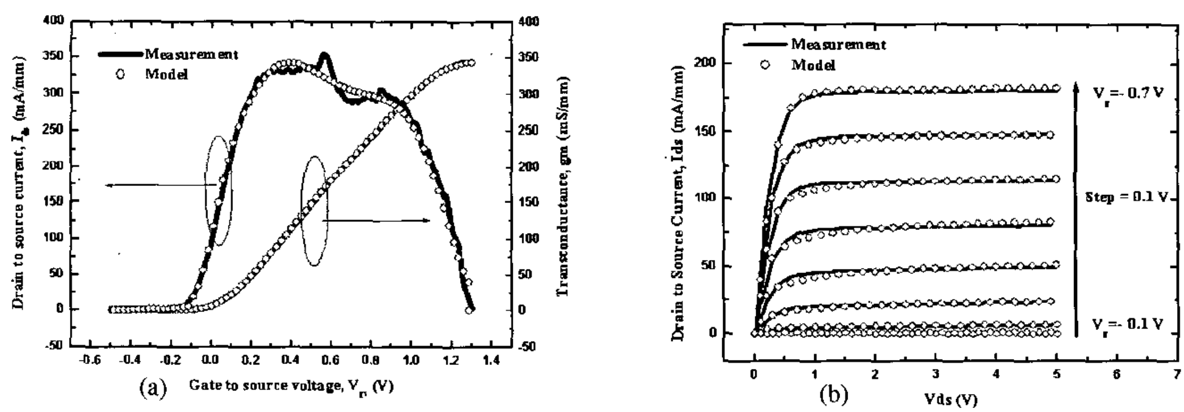

Fig. 2 The measured (lines) and model predicting (dots) dc I-V characteristics of enhancement mode pHEMT with gate length 0.8μm and width 200 μm g_m-I_{ds} characteristics(a) , I_{ds}-V_{ds}(b).

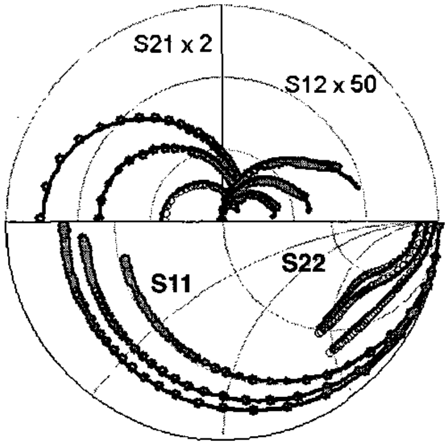

Fig.3 The measured (lines) and model predict (dots) S - parameters from 50MHz to 20.05 GHz at V_{ds} = 3V, V_{gs}=0.3, 0.1, and 0 V

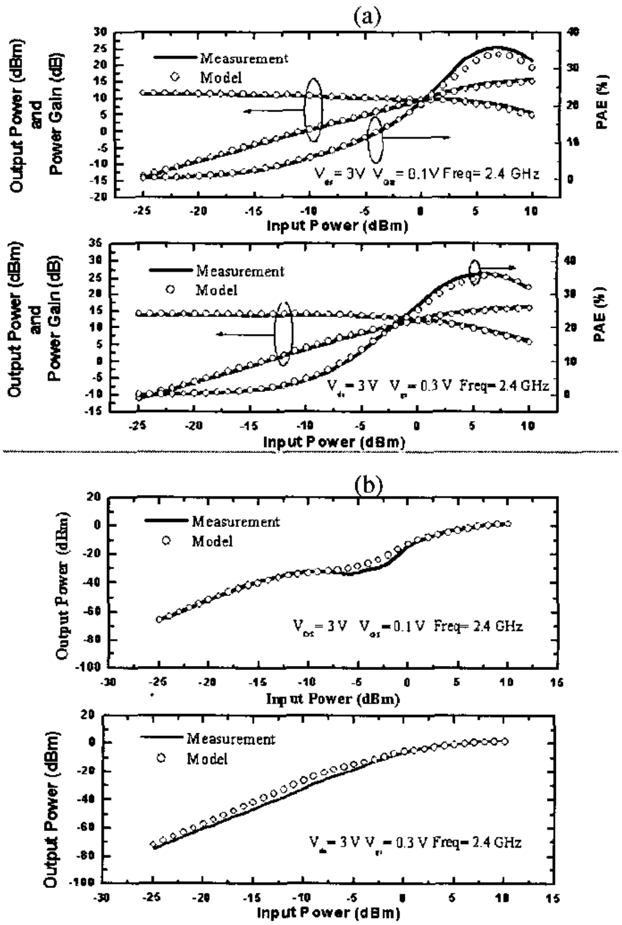

Fig.4 The measured (lines) and model predict (dots) power performance at V_{ds} = 3V, V_{gs}=0.3, 0.1V. 2.4GHz fundamental power (a), 2.4GHz IM3 power(b).

III. THE PREDICTIONS OF POWER PERFORMANCE

This large-signal model can also predict the power performance of the E-pHEMT accurately. The Figs. 4 (a) and 4 (b) show the measured (lines) and molded (dots) at 50 Ω termination. Additionally, for the maximum output power performance and power contour predictions, the load-pull and simulation results are shown in Fig. 5 and Fig.6. The maximum output power and output gamma values are 15.8 dBm and 0.33 $\angle 6.7^{\circ}$ from the load-pull measurement and 16.28 dBm and 0.32 $\angle 12.8^{\circ}$ from the simulation results. The positions of the maximum output power for both modeled and measured results are very close. The comparisons of the maximum output power between the measured and modeled are shown in Fig. 6, and the simulation results agree with the measurement ones.

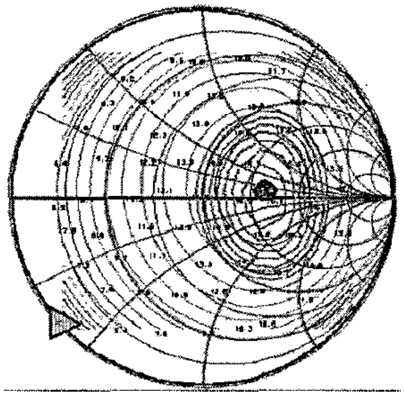

Fig.5 The measured and modeled predictions for power contours a V_{ds} = 3V, V_{gs}=0.3, frequency 2.4GHz, input power 0dBm.

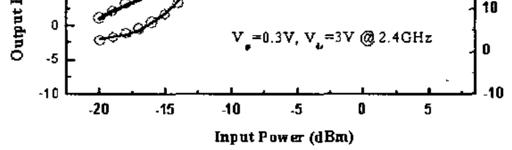

Fig.6 The measured and modeled predictions for maximum power performance at V_{ds} = 3V, V_{gs}=0.3, frequency 2.4GHz.

IV. THE PREDICTIONS OF NOISE PERFORMANCE

The pHEMT device having the advantages of the low noise performance has been demonstrated. It is important and convenient for a circuit designer to have a device model including the noise predictions. Therefore, we add the noise parameters P, R, and C, eqs (8) to (10), [7] into our SDD-based empirical large-signal model, and this approach can predict the NF_{min} and Γ_{opt} very well. As shown in Fig.7 by co-operating the noise parameters and the thermal noise of small-signal model. The P, R, and C are associated with the current noise, i.e. $\overline{i_d^2}$ and $\overline{i_g^2}$, and the correlation between both [9]. The values of P, R, and C are 0.55, 0.47, and 0.15+0.65j for V_{gs}=0.1V, V_{ds}=1.5V and 1.1, 0.89 and 0.192+0.8j for V_{gs}=0.1V, V_{ds}=3V, respectively. The NF_{min} can be as low as 0.4dB at 1GHz and shifts to 1.5dB at 6 GHz. In addition, the predictions of Γ_{opt} can also reach a good agreement.

$$\overline{i_d^2} = 4kT\Delta f g_m P \quad (8)$$

$$\overline{i_g^2} = 4kT\Delta f (2\pi f C_{gs})^2 R / gm \quad (9)$$

$$C = \overline{i_g i_d^*} \Big/ \sqrt{\overline{i_g^2} \cdot \overline{i_d^2}} \quad (10)$$

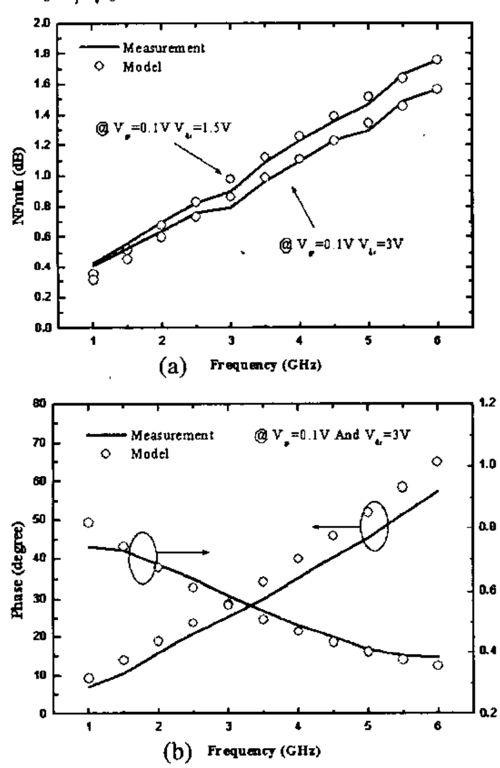

Fig.7 The measured and model predicted NF_{min} at V_{ds} = 3V and 1.5V, V_{gs}=0.1 (a), and Γ_{opt} at V_{ds} = 3V, V_{gs}=0.1 (b)

V. CONCLUSIONS

A complete self-defined large-signal model with noise formulation included for E-pHEMT has been established by using a SDD-based equivalent circuit and polynomial equation descriptions. The dc-IV, S parameters, power performance, inter-modulation, and particular the noise performance can be well predicted, which match the measured data accurately. Therefore, this model is useful in an extensive analysis of a microwave circuit design in wireless communication system.

ACKNOWLEDGMENTS

The authors are grateful to the MOST Co. in Taiwan, for providing E-pHEMTs. This work was partly supported by grant no. 89-E-FA06-1-4 (Pursuing Academic Excellence Developing Project of Universities) from the Ministry of Education, Taiwan, ROC. And also thank to the Nano Device Labs (NDL) for RF load-pull and microwave noise measurements.

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