Paper

PHEMT transistor models for accurate CAD of MMIC amplifiers

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Abstract — Selected models of PHEMT transistors are presented for the popular Philips D02AH process. The models are based on a set of measurements of transistor parameters and have been verified against measurements of fabricated MMIC amplifiers. The usefulness of particular models for the CAD of microwave circuits is discussed.

Keywords — monolithic microwave integrated circuits, transistor modeling.

1. Introduction

Accurate modeling of microwave monolithic integrated circuits (MMICs) is very desirable for the reason of high fabrication costs of GaAs circuits. Designers are trying to achieve the "first trial success" to lower costs and accelerate the introduction of new products. Mature and reliable technology and accurate models of circuit components – active devices in particular – are crucial for the achievement of economic goals. The D0AH process from the Philips Microwave Limeil (PML) foundry has proven to provide reliable and repeatable circuits, as our 4 year experience indicates. The models presented here are based on many measurements of individual transistors and complete MMICs [1]. These results may aid other designers to select proper model and to adjust its parameters appropriately. The emphasis has been placed on nonlinear models capable of accurate prediction of intermodulation distortion. The level of the IM products is one of the most important parameters specified for modern telecommunication circuits.

2. HEMT transistor models for the D02AH process from Philips

Philips foundry provides several models for the PHEMT transistors in the D02AH technology (and the newer version ED02AH) [2]. Small signal linear models are given in the form of tables of circuit parameters versus bias point of a transistor. Nonlinear models are defined by the equations given in the manual as well as models distributed for the Microwave Design System and Cadence CAD systems.

A set of computer programs has been developed at the Institute of Electronic Systems (IES) to implement the linear and nonlinear models defined by the Philips data. The output from these programs provides tables of scattering and noise parameters for particular transistor geometry and selected bias point. Number of MMICs have been designed with these parameters in previous years. The agreement between design and measurements was reasonably good, when typical bias points were used for transistors.

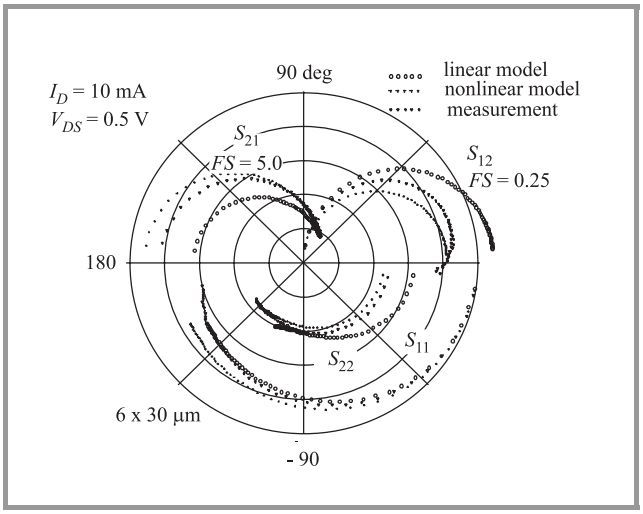

Fig. 1. Comparison of PML models of a FET with measurement.

Comparison of data measured for test transistors with the model parameters discloses discrepancies at low and high currents in particular. Typical results for a transistor with 6 gate segments of 30 μm width each (labeled 6×30) are shown in Fig. 1 for the bias point $I_D = 10$ mA, $V_{DS} = 0.5$ V. The relative error

$$\delta = \frac{S_{ij\,\text{measured}} - S_{ij\,\text{model}}}{S_{ij\,\text{measured}}}$$

can be as high as 30% at selected frequencies. Similar errors are encountered at low drain currents (below 0.1 I_{DSS}). Noise figures of amplifiers designed were typically higher then design by 0.2 dB at a level of 1 dB and as much as 0.5 dB at a level of $NF \approx 3$ dB (for feedback amplifiers). These differences initiated the research into more accurate model definition. The software used for the design of MMICs at the IES is usually the Serenade suite from Ansoft and the models for this software were investigated in more detail.

3. Nonlinear microwave FET models for the Serenade software

Nonlinear simulator (Microwave Harmonica – M-H) from the Serenade suite of CAD software [3] is implementing several nonlinear models of microwave FETs. Two models

have been selected for further use: a model by Kacprzak and Materka [4] (labeled K-M in subsequent text) and a model from the Triquint foundry [5] – labeled TOM2. These models are known to provide high accuracy in the computation of nonlinear properties of amplifiers (e.g. intermodulation).
General chip model – excluding package – of a microwave FET in the M-H program is shown in Fig. 2. Its internal nonlinear portion is specific to the model used.

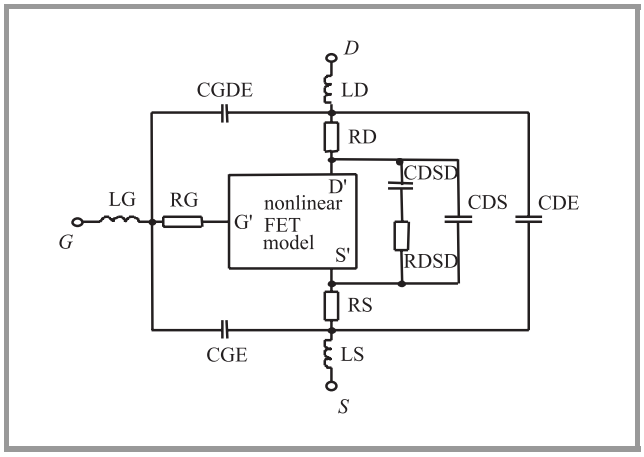

Fig. 2. General FET transistor model in Microwave Harmonica.

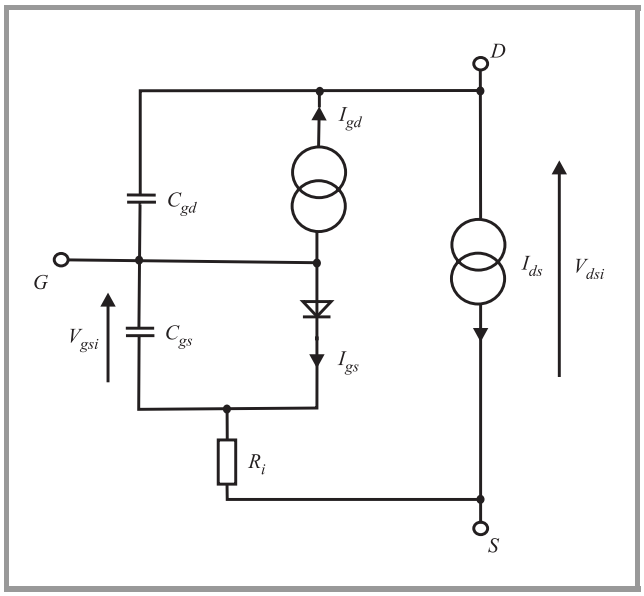

Fig. 3. Kacprzak-Materka FET model.

The structure of the K-M model is presented in Fig. 3. Static response of a drain current versus internal voltages V_{gsi}, V_{dsi} is characterized by a set of parameters listed below:
IDSS – saturation current for $V_{GS} = 0$, $VP0$ – pinch-off voltage for $V_{DS} = 0$, *GAMA* – slope parameter versus V_{dsi} for $VP0$, E – constant part of power law parameter $I_D(V_{gsi})$, *KE* – dependence of power law on V_{gsi}, *SL* – slope of the drain characteristic in the linear region, *KG* – dependence of V_{gsi} on V_{dsi} in the linear region, *SS* – slope of the $I_D(V_{DS})$ char. in the saturated region.
Drain current for the K-M model is given by:

$$I_{ds} = IDSS\left(1 + SS\frac{V_{dsi}}{IDSS}\right) \times \times \left(1 - \frac{V_{gsi}}{VPO + GAMA \cdot V_{dsi}}\right)^{(E + KE \cdot V_{gsi})} \times \times \tanh\left(\frac{SL \cdot V_{gsi}}{IDSS(1 - KG \cdot V_{gsi})}\right). \quad (1)$$

Triquint TOM2 model is depicted if Fig. 4 and its set of DC parameters is explained below:
BETA – transconductance coefficient, $VT0$ – pinch-off voltage, U – mobility degradation fitting parameter, *GAMA* – slope parameter of $VT0$ (versus V_{dsi}), Q – power law parameter for $I_D(V_{gsi})$, *NG*, *ND* – subthreshold slope parameters for $I_D(V_{gsi}, V_{dsi})$, *DELT* – slope of $I_D(V)DS)$ in the saturated region, *ALFA* – slope of $I_D(V_{DS})$ in the linear region.

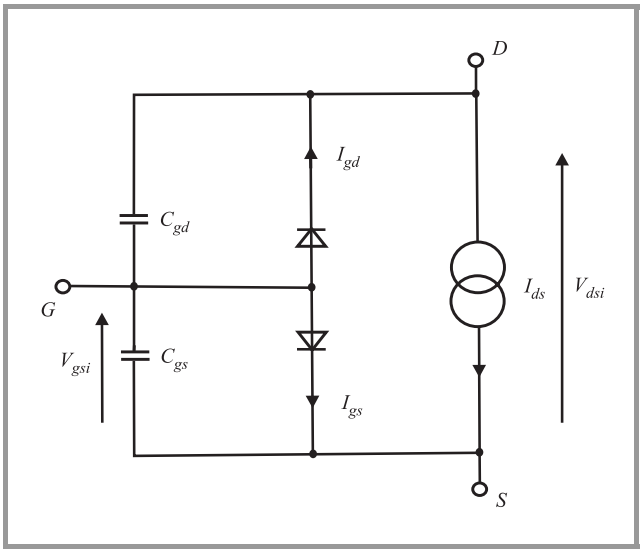

Fig. 4. TOM-2 model.

These parameters are used in a set of Eqs. (2) which define the drain current as a function of voltages V_{dsi}, V_{gsi}.

$$I_{ds} = \frac{I_{ds0}}{1 + DELT \cdot I_{ds0} \cdot V_{dsi}}$$
$$V_{gst} = V_{gsi} - VT0 + GAMA \cdot V_{dsi}$$
$$I_{ds0} = \frac{\mathrm{B}}{1 + U \cdot V_{gsi}} V_g^Q KTanh$$
$$V_g = Q \cdot V_{st} \ln\left[\exp\left(\frac{V_{gst}}{Q \cdot V_{st}}\right) + 1\right]$$
$$V_{st} = (NG + ND \cdot V_{dsi}) V_t$$
$$KTanh = \frac{ALFA \cdot V_{dsi}}{\sqrt{1 + (ALFA \cdot V_{dsi})^2}}. \quad (2)$$

A computer program was written to identify parameters of both models to fit the measured DC curves and also scattering parameters for a range of bias point values. The program first matches the DC characteristics of the model. Then the model parameters responsible for its DC properties (including *RS* and *RD* resistances) are fixed and the parameters relevant for the AC small signal response are found. These include the coefficients in capacitance equations, parasitic capacitances and inductances (see Fig. 2). Typical definitions of both models for the M-H program are given next.

For a transistor with the total gate width of 180 μm (6 segments 30 μm wide) the K-M model is as follows:

.model D02AH FET (IDSS=0.046077 SS=0.006156
+VP0=-0.744190 GAMA=-0.092446 E=1.141426
+KE=-2.508094 SL=0.334809 KG=0.455653
+RS=6.02 RD=3.790510 CLVL=2 CGS0=0.172254pF
+CGD0=0.0377342pF VBI=0.4454390
+CDS=0.0240132pF R10=1.9680642 KR=0.2275464
+RG=6.7097157 CGE=0.0270697pF CDE=0.0058621pF
+CGDE=0.0046914pF LG=0.0202468nH
+LD=0.0291279nH LS=0.0097873nH
T=0.1784086ps TJ=300 VMAX=0.5 VDMX=-3.0).

Triquint TOM2 model for the same transistor is as follows:

.model D02AH FET (BETA=0.138751
+VT0=-0.557976 U=0.002805 GAMA=0.053786
+Q=1.486948 NG=1.660377 ND=0.080267
+DELT=1.178524 ALFA=7.025695 RS=4.73-0066
+RD=3.888-889 CGS0=0.-12pF CGD0=0.048pF
+IS=1.5pA T=1E-12 LG=15pH LD=8.83pH
+LS=3.22pH CDE=21.514fF CGE=6.68fF
+CGDE=0.004pF +RDSD=903.4 CDSD=264.28pF
VDMX=3.0).

Selected measured characteristics of PHEMT transistors from the D02AH process are compared in Figs. 5 – 8 with various models evaluated. MDS denotes results from the *Microwave Design System* (HP) for the library models provided by PML.

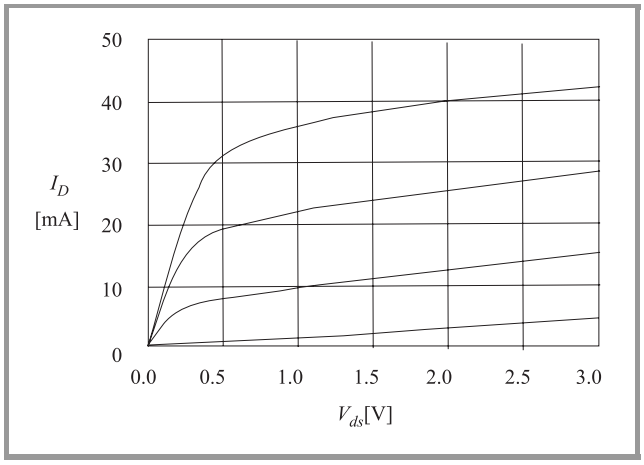

Fig. 5. Modeling of output characteristics of a 6×30 μm FET.

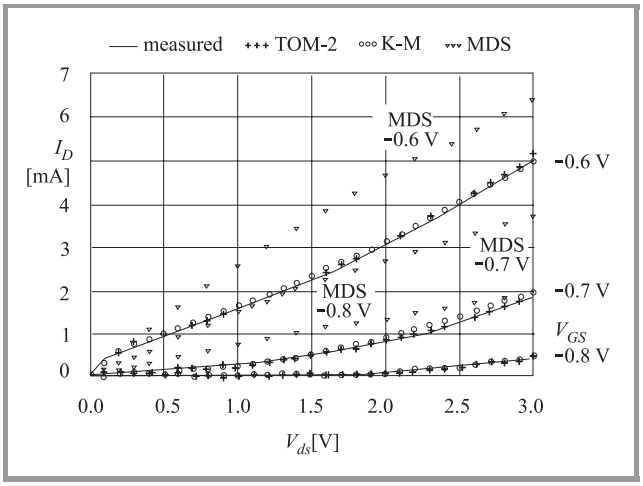

Fig. 6. Low current range for $I_D(V_{DS})$ curves modeling.

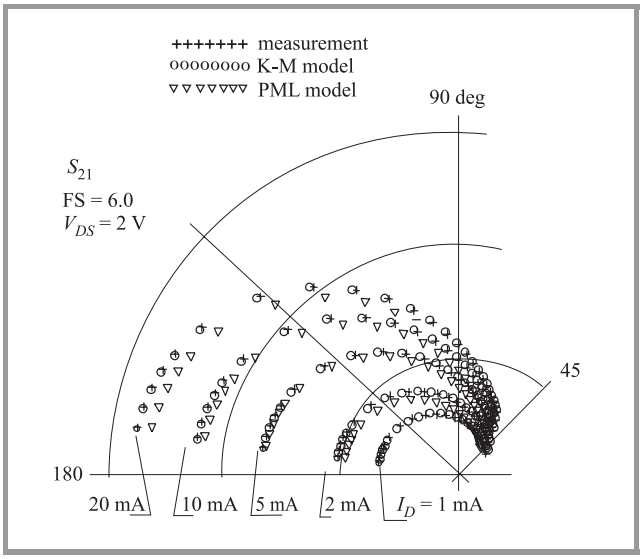

Fig. 7. S_{21} versus frequency and drain current. Transistor 6×30 μm, frequency range: $1 - 40$ GHz.

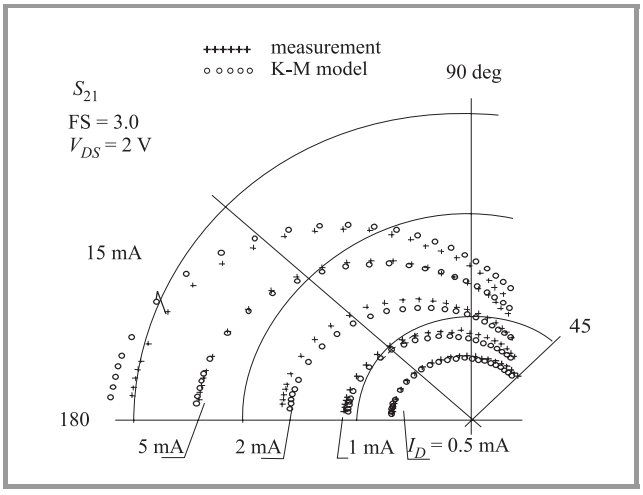

Fig. 8. S_{21} versus frequency and drain current. Transistor 6×15 μm transistor: $f = 1 - 40$ GHz.

Both K-M and TOM2 models predict the DC characteristics very accurately over broad range of currents and voltages. TOM2 model is slightly more accurate in this respect. Philips model for MDS is not very accurate, particularly at low drain voltages. Small signal parameters generated from the K-M model provide average relative error δ on the order $2-4\%$, with slightly greater errors for high drain current. It has to be mentioned that none of the models makes provision for the dynamic changes in chip temperature. This is the main reason of discrepancies at higher I_D and V_{DS} bias points – both for DC and small signal characteristics. Such improved models could certainly be developed, but it was not the aim of this work to create new models, but to improve existing ones for the popular microwave CAD packages. Tests on real circuits presented next prove that very good agreement may be achieved with the models precisely identified.

4. Experimental verification of models

Several amplifiers designed at the IES have been evaluated with the models presented. An example of a simple two stage L-Band amplifier (Fig. 9) is presented below. Transmission parameters S_{21} and S_{12} are compared in Fig. 10 and IM distortion measurements and modeling are presented in Figs. 11 and 12. IM test were performed with two equal signals at input with frequencies $f_1 = 1000$ MHz and $f_2 = 1010$ MHz.

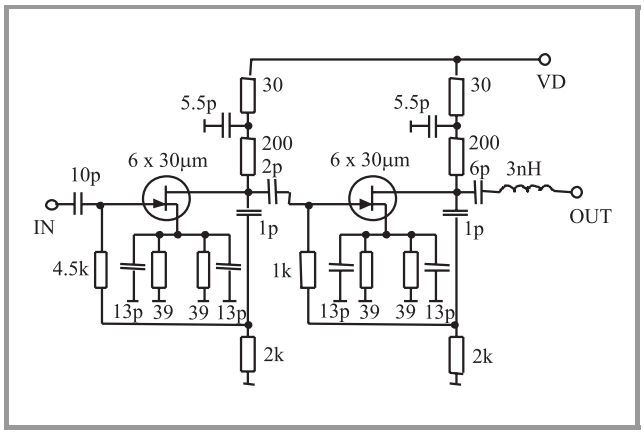

Fig. 9. Simplified circuit diagram of the LNAMP134 amplifier.

Both models (Kacprzak-Materka and TOM2) provide quite precise simulation of both small signal and nonlinear properties of MMIC amplifiers. When model parameters are appropriately identified, i.e. fitted to actual transistor parameters, accurate prediction is possible for operation in the saturation region as well as in the linear region of the FET bias. K-M model proved to be more accurate in prediction of the intermodulation distortion of microwave amplifiers and therefore it has been subsequently used for the design of more advanced MMICs at the Warsaw University of Technology.

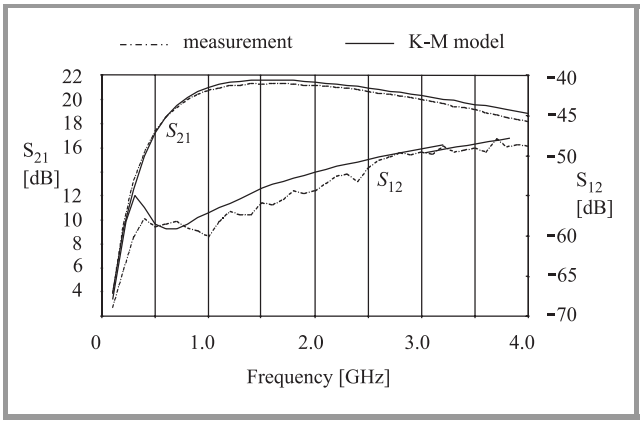

Fig. 10. Forward ($|S_{21}|$) and reverse ($|S_{12}|$) transmission modeling for the LNAMP134 MMIC.

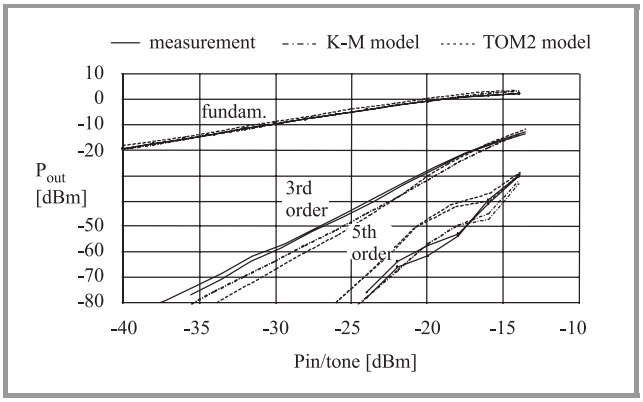

Fig. 11. Intermodulation distortion – measurement and modeling for $V_D = +6$ V.

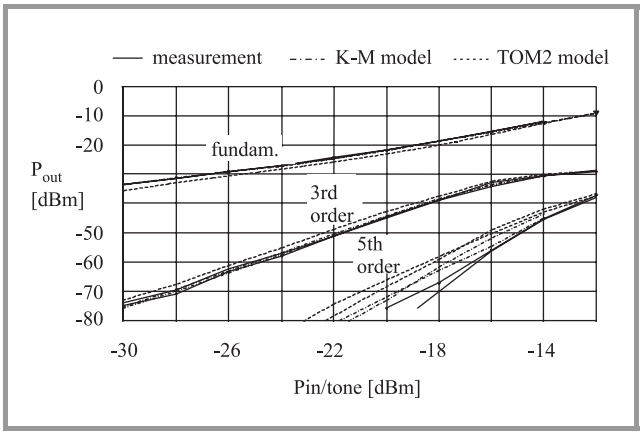

Fig. 12. Intermodulation distortion comparison for $V_D = +3$ V.

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References

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