Unique and physically meaningful extraction of the bias-dependent series resistors of a 0.15 μm PHEMT demands extremely broadband and highly accurate measurements

M. Novotny, and G. Kompa, *Member, IEEE*

Universität Kassel, Fachgebiet Hochfrequenztechnik (HFT)
Wilhelmshöher Allee 73, D-34121 Kassel, Germany

ABSTRACT

In addition to known extraction results this paper is focusing on the bias-dependence of the series resistors of a 0.15μm PHEMT with physics-related values. It is shown that nearly all model parameters of a 20-element device model can be obtained applying known fitting procedures. However taking into account nowadays available measurement uncertainties this approach fails in the determination of the bulk resistors R_s and R_d. Therefore a novel highly sensitive two-frequency parameter extraction procedure is proposed. Based on simulation and experimental data it is shown that S-parameter data at least above 70 GHz are needed to obtain reliable results. The extracted frequency-dependent element value distribution directly reflects the measurement uncertainties.

INTRODUCTION

The reliable small-signal parameter extraction of microwave FET models is essential for the experimental nonlinear device modeling [1]. The FET model consists of external linear and internal non-linear frequency-independent model elements. Knowing the accurate values of the parasitics, the nonlinear device modeling process is tremendously simplified and restricted to the inner part with reduced number of model elements.

Numerous papers have dealt with the subject of model parameter extraction for many years concerning mainly FET devices with moderate gate lengths of about 0.25 - 1 μm [2]. Typically an equivalent circuit topology of 15 elements has been used for the simulation of the electrical behavior of the device. A multi-bias extraction procedure has been proposed recently that delivers consistent model element values using S-parameter data up to 40 GHz [3]. All extraction procedures, known so far, assume constant bulk resistors R_s and R_d, i.e. bias-independent resistive elements. This assumption is not clear and often controversially discussed.

In this paper the modeling of a 0.15μm PHEMT is investigated based on measured S-parameter data up to 120 GHz [4]. All model elements are derived from scattering parameters in the passive pinch-off and saturation region. Critical FET operation in the gate forward direction is not required.

SUB-0.2μm-FET MODEL

As our investigations have shown the classical 15-element model cannot be used to equivalently describe the broadband electrical behavior of a sub-0.2μm FET especially at higher frequencies up to 120 GHz. Nevertheless satisfying agreement between simulated and measured S-parameter data may be achieved, however, under the deficiency of extracted unphysical zero or negative values for the bulk series resistors.

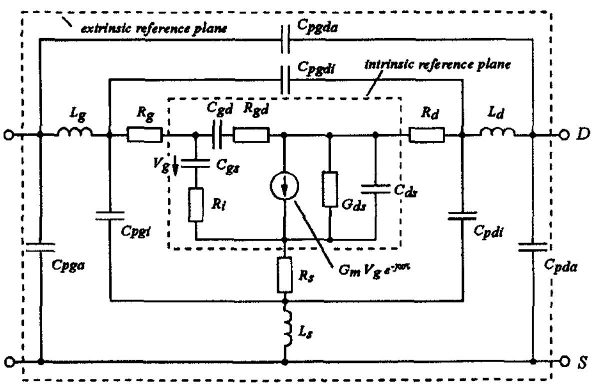

Fig. 1: Defined small signal equivalent circuit for modeling a 0.15 μm PHEMT (saturation region).

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Thus, we had to refine the model topology. As Fig. 1 illustrates, the extended model for the saturation region contains 20 elements. In the passive pinch-off region ($V_{GS} > V_{po}$ and $V_{DS} = 0$ V) it can be simplified by neglecting the drain current source, the channel conductance G_{ds} and the drain source capacitance C_{ds}. The bulk resistor R_d and the gate-drain resistor R_{gd}, as well as the charging-resistor R_i and source resistor R_s can then be put together to an effective gate resistor R_{gd}', and an effective charging resistor R_i', respectively.

C_{pgi}, C_{pdi} and C_{pgdi} describe the parasitic capacitors between the gate-, drain- and source-electrodes. C_{pga}, C_{pda} and C_{pgda}, located at the periphery of the equivalent network, model the capacitive effects which results from the contacting measurement probes.

EXTRACTION PROCEDURE

In a first extraction step the bias independent parasitics are determined from measured 120 GHz S-parameter data in the passive pinch-off operating point. A fundamental extraction problem originates in the consistent determination of the values of C_{pga} and C_{pgi}, C_{pda} and C_{pdi}, and C_{pgda} and C_{pgdi}. Because of the small values of the inductances and the external capacitances it is in general not possible to find a unique solution for the shunted elements. The sum of the element values turns out to be stable, however, the separation is arbitrary. As the external capacitors describe the contacting situation of the used Cascade prober, C_{pgda}, C_{pga} and C_{pda} have only low values in the order of some fF's. Therefore, we ignored them first in the optimization process which is based on the modified Simplex algorithm [5]. We introduced a compound error function comprising sub-error functions with respect to the external and the intrinsic device reference planes. It has turned out that the sensitivity of the total error function could significantly be increased. The extraction results show that the values of the capacitors C_{pgdi} and C_{pgda} are negligible small. For reason of symmetry of the device geometry C_{gs} and C_{gd} can be set equal at the regarded bias point.

Table 1
Starting value intervals for random optimization

C_{pgi}, C_{pdi} / fF	3-30	R_g / Ω	1 - 10
L_g, L_d / pH	10-50	R_i', R_{gd}' / Ω	1 - 20
L_s / pH	10-20	C_{gs}, C_{gd} / fF	10 - 50

A random optimization has been carried out for 100 starting vectors randomly generated within the starting value intervals shown in Table 1.

The first two columns in Table 2 show the extraction results and the standard deviation for each model element.

Table 2
Extraction results and standard deviation for the random optimization

	Simplified Circuit without C_{pga} and C_{pda}		Pinch-Off Circuit with C_{pga} and C_{pda}
	Mean Values	Standard Deviation	Element Values
C_{pga} / fF	—	—	3.34
C_{pda} / fF	—	—	2.69
C_{pgi} / fF	7.2	0.09 %	4.02
C_{pdi} / fF	26.3	0.09 %	24.1
L_g / pH	36.6	0.1 %	37.5
L_d / pH	29.7	0.2 %	29.9
L_s / pH	1.4	2.9 %	3.29
R_g / Ω-mm	0.17	2.6 %	0.16
C_{gs} / pF/mm	0.31	0.06 %	0.31
C_{gd} / pF/mm	0.31	0.06 %	0.31
R_i' / Ω-mm	0.79	1.2 %	0.71
R_{gd}' / Ω-mm	1.82	0.8 %	1.53

It can be seen that all elements have been extracted with high consistence. In a following optimization step the small extrinsic capacitors C_{pga} and C_{pda} are included, and all model elements are re-optimized. It can be seen from the 3rd column of Table 2 that the values of the elements are nearly the same. However, C_{pgi} and C_{pdi} have been decreased in favor of the shunted C_{pga} and C_{pda}, whose values of only a few fF are very realistic for the modeling of the prober connections.

DETERMINATION OF THE SERIES RESISTORS R_s and R_d

As is well known the resistors R_s and R_d have only slight influence on the curve traces of the frequency-dependent S-parameters. One motivation for unique and physically meaningful determination of the resistors values is the simulation of noise performance. Furthermore the transconductance G_m and R_s correlate with each other. Determination of R_s under gate forward condition may result in a lower resistance value which would lead to an over-estimated internal transconductance value of G_m.

We have intensively analyzed the extraction feasibility of the resistors both by synthetic and measured S-parameters.

Fig. 2 shows the error function for the relative difference between synthetic and optimized S-parameters in dependence of R_d and R_s. The true values were chosen as $R_d = R_s = 5$ Ω. As can be seen the 3d-plot shows a clear minimum for the expected values of the resistors. The dependence from R_d is very small. The changing from R_s

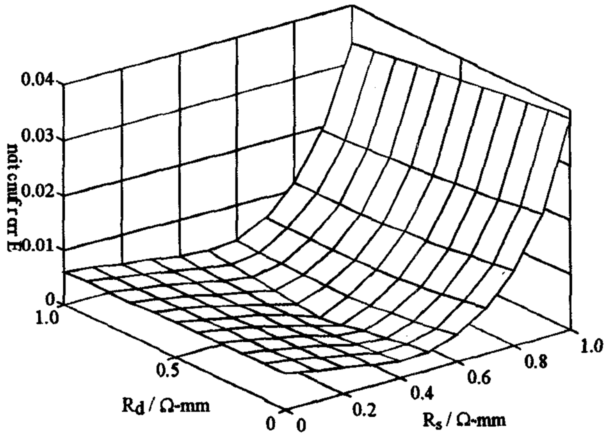

Fig. 2: Error function versus R_d and R_s for synthetic S-parameters.

is much more sensitive. This implies that the value of R_s has a big influence on the intrinsic equivalent circuit elements.

Regarding real measurement data no minimum for R_d and R_s can be detected (Fig.3). It can be concluded that the common extraction method taking into account S-parameter data at numerous frequencies over a broadband frequency range is not practicable for R_s and R_d extraction. It could be shown that the general requirement for successful extraction of frequency independence of the extracted model parameters could be fulfilled for a lot of different combinations of R_d and R_s. Our experience is that the frequency independence of the elements is a necessary but not sufficient condition for a physically relevant equivalent circuit extraction.

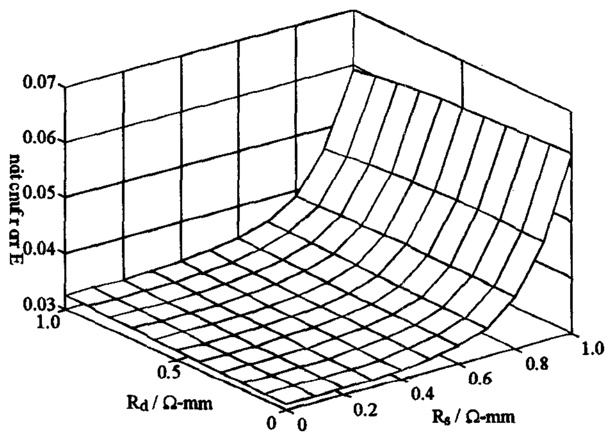

Fig. 3: Error function versus R_d and R_s for measured S-parameters.

To circumvent the resistor extraction problems we applied a new two-frequency extraction procedure. Optimization is performed on the basis of only two frequencies, involving a fixed low frequency at 0.5 GHz.

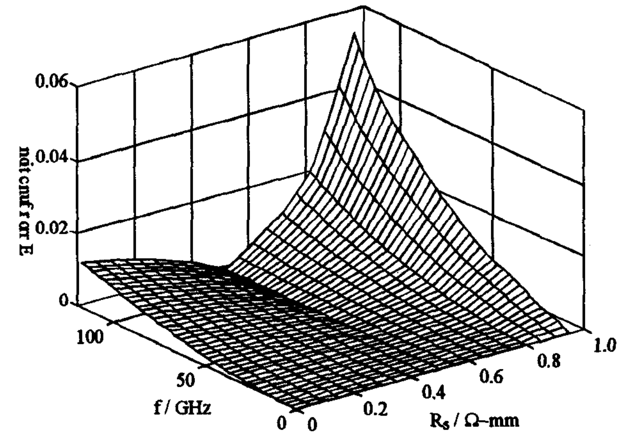

Fig. 4: Error function versus f and R_s for synthetic S-parameters.

Regarding synthetic S-parameters with R_s = 5 Ω, Fig. 4 shows the compound error function in dependence of the frequency and the value of R_s. It can be clearly seen that measurement data are needed in the order of 100 GHz to extract R_s reliably.

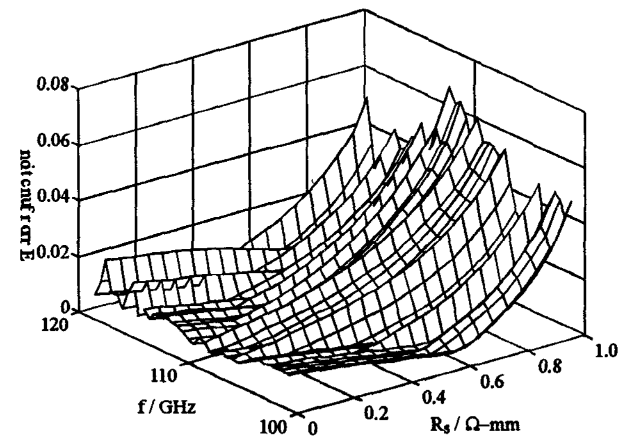

Fig. 5: Error function versus f and R_s for measured S-parameters.

Fig. 5 shows the error function for real measurement data for frequencies between 100 and 120 GHz. It can be seen that the extracted values of R_s differs in the range of 0.4 - 0.6 Ω-mm, reflecting the measurement uncertainties.

More sensitive analysis can be performed regarding the partial error functions with respect to the individual S-parameters. Fig. 6 shows a best possible extraction situation at a frequency of 117 GHz. It can be seen that all error functions have a minimum at the same value of R_s. Such concurrent conditions imply small measurement uncertainties. In other cases the minimums will scatter.

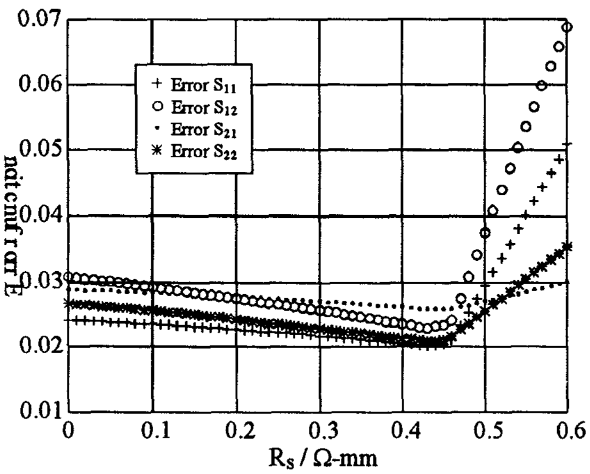

Fig. 6: Error functions for S_{11}, S_{12}, S_{21} and S_{22} versus R_s for f = 117 GHz.

BIAS-DEPENDENT R_s

S-parameters have been measured for several operating points (V_{DS} = 0.5(0.5)2.5 V; V_{GS} = -0.4(0.2)0.4 V) in a frequency range of 0.5 - 120 GHz to analyze the behavior of the bias dependent model elements, including R_s.

The extracted bias dependence of R_s is shown in Fig. 7. The value decreases from pinch-off towards passive gate forward. The known extrinsic elements derived from the passive pinch-off region and the bias dependent values for R_s, which have a great influence on the intrinsic FET elements, now allow an exact calculation of the intrinsic elements using the analytic formulas given in Ref. [3]. An excellent agreement between measured and calculated S-parameters can be achieved in particular at frequencies above 100 GHz. In addition it could be shown that the frequency independence of the intrinsic elements is fulfilled.

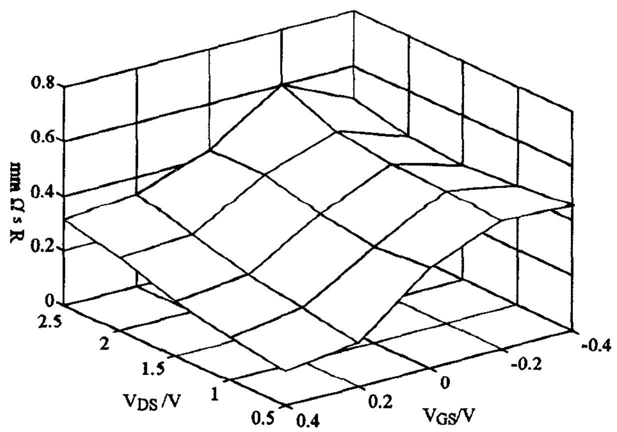

Fig. 7: Determined dependence of R_s versus V_{GS} and V_{DS}.

CONCLUSIONS

In this paper we have mainly discussed the difficulties in the extraction of the series resistors R_d and R_s of a 0.15μm-PHEMT on the base of nowadays available measurement techniques and uncertainties. It has been shown that the resistors cannot be determined by a common overall fitting procedure. Using the proposed new two-frequency extraction procedure it has been demonstrated that R_s can be determined uniquely. The distribution of the extracted results directly reflect the uncertainties of the measurement. This should be continuously improved for further extraction optimization and to make R_d-extraction possible in future, too.

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REFERENCES

[1] G. Kompa: "Modeling of Dispersive Microwave FET Devices using a Quasi-Static Approach," *Int. J. of Computer-Aided Engineering (MMWCAE)*, Vol. 5, No. 3, pp. 173-194, 1995.

[2] G. Dambrine, A. Cappy, F. Heliodore, and E. Playez: "A New Method for Determinating the FET Small-Signal Equivalent Circuit," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 1151-1159, July 1988.

[3] F. Lin, G. Kompa: "FET Model Parameter Extraction Based on Optimization With Multiplane Data-Fitting and Bidirectional Search - A New Concept," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-42, pp. 1114-1121, July 1994.

[4] P.J. Tasker, J. Braunstein: "New MODFET Small Signal Circuit Model Required for Millimeter-Wave MMIC Design: Extraction Validation to 120 GHz," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1995, pp. 611-614.

[5] G. Kompa, M. Novotny: "Highly Consistent FET Model Parameter Extraction Based on Broadband S-Parameter Measurements," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Albuquerque, NM, 1992, pp. 293-296.