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STATISTICAL MODELING OF GaAs MESFETs

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ABSTRACT

This paper contrasts the statistical extraction of GaAs MESFET equivalent circuit model parameters and physical model parameters from wafer measurements. We observe that the Materka and Kacprzak model based on equivalent circuit parameters provides a better match for individual devices, but the Ladbrooke model based on physical parameters provides a better estimate of device statistics.

INTRODUCTION

Statistical modeling is a prerequisite for yield-driven and cost-driven circuit optimization [1,2]. Purviance *et al.* [2] investigated the use of FET equivalent circuit model parameter statistics in circuit design. However, the ability of equivalent circuit models to reflect the actual device statistics is questionable [3]. Purviance *et al.* proposed [3] to rely on individual models obtained from measured data without extracting sample statistics. This approach, however, is limited by the actual measurement sample size.

In this paper, we present a study on statistical modeling of GaAs MESFETs at the equivalent circuit model parameter level and the physical model parameter level. We contrast the Materka and Kacprzak equivalent circuit model [4] with the Ladbrooke model [5] which is defined in terms of physical parameters. The model parameters are extracted from GaAs MESFET wafer measurements provided by Plessey Research Caswell [6]. The measurements consist of DC bias data and multi-bias S parameters from a sample of GaAs MESFET devices. The parameter extraction and statistical postprocessing are automated by the statistical modeling features of HarPE™ [7].

Our results show that modeling at the equivalent circuit parameter level is more flexible and therefore may provide a better match for individual devices. But the Materka and Kacprzak model with equivalent circuit parameter statistics failed to reproduce the sample statistics of the measured data. In contrast, the Ladbrooke model at the physical parameter level can provide a better estimate of the statistical spread of the measurements.

THE GaAs MESFET MODELS

A. The Materka and Kacprzak Nonlinear Equivalent Circuit Model

The Materka and Kacprzak model [4] is a nonlinear equivalent circuit model which is defined directly using circuit model parameters. The model parameters to be extracted include the nonlinear intrinsic FET parameters

$$\{I_{DSS}, V_{p0}, \gamma, E, K_E, \tau, S_S, R_{10}, K_R, C_{10}, C_{1S}, K_1, C_{F0}, K_F\}$$

and the linear extrinsic parameters

$$\{L_G, R_G, R_D, L_D, R_S, L_S, G_{DS}, C_{DS}\}.$$

Some of the model parameters are not involved because they are related to the large-signal nonlinear characteristics of the model and have little influence on the responses of interest here.

B. The Ladbrooke Physics-Based Equivalent Circuit Model

The Ladbrooke model [5] also uses an equivalent circuit, as shown in Fig. 1. But the equivalent circuit and its components are derived from the physical parameters and the bias conditions, such that the model is defined in terms of the device physical parameters. From the analysis of the MESFET device [5], the equivalent depletion depth d is obtained as

$$d = [2\epsilon(-V_{G'S'}+V_{B0})/(qN)]^{0.5}, \tag{1}$$

the voltage dependent space-charge layer extension X as

$$X = a_0\{2\epsilon/[qN(-V_{G'S'}+V_{B0})]\}^{0.5}\,(V_{D'G'}+V_{B0}), \tag{2}$$

and the channel current is calculated as

$$I_{CH} = qNv_{sat}(W-d)Z_G \tag{3}$$

where ϵ is the dielectric constant, V_{B0} the zero-bias barrier potential, q the electron charge, N the doping profile, v_{sat} the saturated value of electron drift velocity, W the channel thickness, Z_G the gate width, and a_0 is a proportionality coefficient. $V_{G'S'}$ and $V_{D'G'}$ are DC voltages from *G'* to *S'* and from *D'* to *G'*, respectively, as shown in Fig. 1.

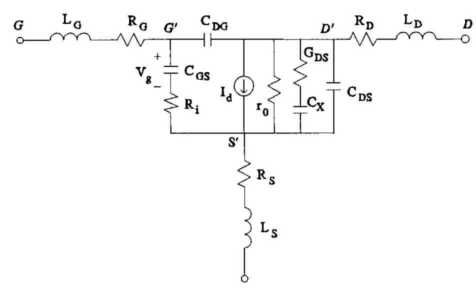

Fig. 1 Topology for the Ladbrooke GaAs MESFET small-signal model where $I_d=g_mV_ge^{-j\omega\tau}$.

In Fig. 1, g_m, τ, r_0, C_{GS}, C_{DG}, R_i, R_D, R_S, and L_G are functions of the physical parameters and bias conditions. For example [5],

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$$g_m = \epsilon\, v_{sat} Z_G / d \quad (4)$$

$$C_{DG} = 2\epsilon\, Z_G/(1+2X/L_{g0}) \quad (5)$$

$$L_G = \mu_0\, dZ_G/(m^2 L_{g0}) + L_{G0} \quad (6)$$

where L_{g0} is the gate length, μ_0 the permeability of free space, m the number of gate fingers, and L_{G0} is introduced to include the inductances from gate bond wires and pads. We approximate the drain output resistor r_0 by

$$r_0 = r_{01}\, V_{D'S'}(r_{03} - V_{G'S'}) + r_{02}. \quad (7)$$

R_G, L_D, L_S, G_{DS} and C_{DS} are assumed to be linear components. Therefore, the model parameters to be extracted are

$$\{L_{g0}, W, N, v_{sat}, V_{B0}, a_0, r_{01}, r_{02}, r_{03}, L_{G0}, R_G, L_D, L_S, G_{DS}, C_{DS}\}.$$

STATISTICAL MODELING

From the sample of GaAs MESFET measurements provided by Plessey Research Caswell [6], we use 69 individual devices (data sets) from two wafers. Each device represents a four finger 0.5μm GaAs MESFET with equal finger width of 75μm. Each data set contains small-signal S parameters measured under three different bias conditions and at frequencies from 1GHz to 21GHz with a 0.4GHz step. DC drain bias current is also included in the measurements.

We use HarPE [7] to extract the statistical device models. The measurements used for parameter extraction include DC bias currents at three bias points and the S parameters for those bias points at frequencies from 1GHz to 21GHz with a 2GHz step. The linear parameter C_X is fixed at 2pF for both models.

We first extract model parameters for each individual device by matching simultaneously the DC and small-signal S parameter responses to the corresponding measurements [8]. The resulting sample of 69 models is postprocessed to obtain the mean values of the parameters. The same procedure was repeated once using the mean values as new initial parameter values. After postprocessing, we obtained the parameter statistics, including the mean value, standard deviation and discrete distribution function (DDF) for each parameter, as well as the correlations among the parameters [9]. The postprocessing is automated by the statistical modeling feature of HarPE.

The parameter statistics (mean values and standard deviations) of the Ladbrooke model and those of the Materka and Kacprzak model are listed in Table I. Fig. 2 illustrates the histograms of the FET gate length L_{g0} (a parameter of the Ladbrooke model) and I_{DSS} (a parameter of the Materka and Kacprzak model).

The postprocessed statistical model can be used for nominal and Monte Carlo simulations. In a Monte Carlo simulation, statistical outcomes are generated from the parameter statistics. In a nominal simulation, the parameters assume their mean values. Fig. 3 shows the match between the S parameters computed from a nominal simulation (i.e., the parameters assume their mean values) and the mean values of the measured S parameters at the bias point V_{GS}=0V and V_{DS}=5V. Excellent fit by the Materka and Kacprzak model and a good agreement by the Ladbrooke model can be observed. This indicates that modeling at the equivalent circuit parameter level is more flexible and therefore can provide a better match for individual devices.

MODEL VERIFICATION

For statistical modeling to be useful in yield analysis and optimization, we must be able to predict the statistical behaviour of the actual devices through Monte Carlo simulation, i.e., the model responses and the actual device responses must be statistically consistent.

To this end we compare the statistical characteristics of the S parameters of the extracted MESFET models with the measurements. The comparison is made at the bias point V_{GS}=0V and V_{DS}=5V and at the frequency 11GHz. For Monte Carlo simulation, we generate 400 outcomes from the mean values, standard deviations, correlations and DDFs of the model parameters [9].

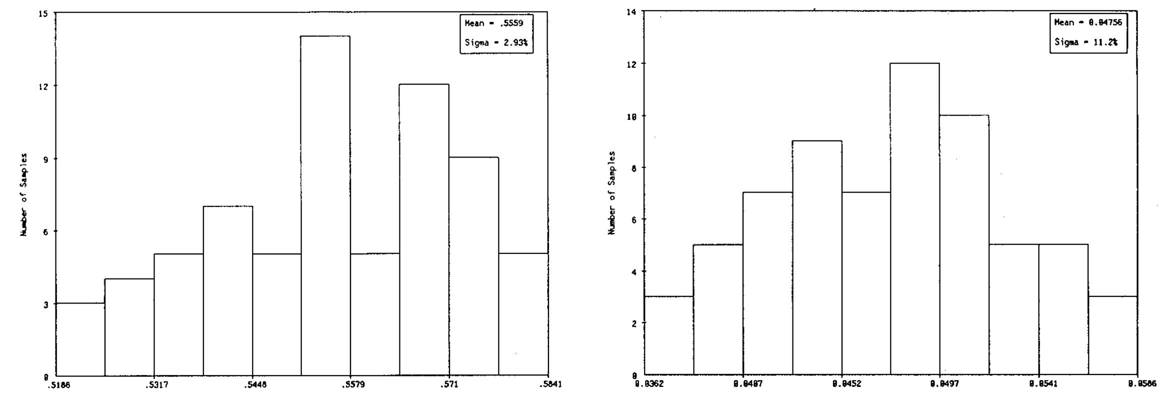
TABLE I

STATISTICAL PARAMETERS FOR THE LADBROOKE AND THE MATERKA AND KACPRZAK MODELS

Ladbrooke Model			Materka and Kacprzak Model		
Para.	Mean	Dev.(%)	Para.	Mean	Dev.(%)
$L_{g0}(\mu m)$	0.5558	2.93	$I_{DSS}(mA)$	47.56	11.2
$W(\mu m)$	0.1059	3.64	$V_{p0}(V)$	-1.488	11.9
$N(m^{-3})$	3.140E23	1.71	γ	-0.1065	7.51
$v_{sat}(ms^{-1})$	7.608E4	3.48	E	1.661	2.40
$V_{B0}(V)$	0.6785	4.94	$K_E(1/V)$	4.676E-3	5.70
a_0	1.031	7.03	$\tau(pS)$	2.187	3.45
$r_{01}(1/A^2)$	1.090E-2	0.44	$S_S(1/\Omega)$	1.565E-3	9.75
$r_{02}(V)$	628.2	6.86	$R_{10}(\Omega)$	7.588	7.40
$r_{03}(\Omega)$	13.99	0.44	$K_R(1/V)$	0.3375	16.9
$L_{G0}(nH)$	2.414E-2	20.7	$C_{10}(pF)$	0.3698	3.55
$R_G(\Omega)$	3.392	4.99	$C_{1S}(pF)$	1.230E-3	28.5
$L_D(nH)$	6.117E-2	18.6	$K_1(1/V)$	1.238	8.73
$L_S(nH)$	2.209E-2	10.6	$C_{F0}(pF)$	1.625E-2	4.57
$G_{DS}(1/\Omega)$	2.163E-3	2.72	$K_F(1/V)$	-0.1180	3.17
$C_{DS}(pF)$	5.429E-2	2.71	$L_G(nH)$	3.422E-2	17.8
			$R_G(\Omega)$	9.508E-3	7.73
			$R_D(\Omega)$	2.445	32.8
			$L_D(nH)$	5.035E-2	28.6
			$R_S(\Omega)$	0.7753	40.2
			$L_S(nH)$	1.427E-2	21.9
			$G_{DS}(1/\Omega)$	1.838E-3	5.02
			$C_{DS}(pF)$	5.838E-2	3.35

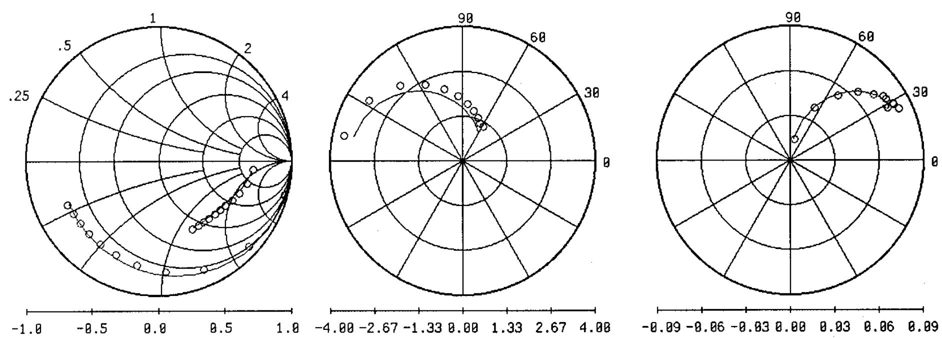
The mean values and standard deviations of the measured S parameters and the simulated S parameters from the Ladbrooke model and from the Materka and Kacprzak model are listed in Table II. We can see from Table II that the standard deviation match given by the Ladbrooke model is good, while large mismatches by the Materka and Kacprzak model exist. On the other hand, the mean value match for the Materka and Kacprzak model appears to be much better than that for the Ladbrooke model. However, the mean value discrepancies for the Ladbrooke model in Table II are consistent with the S parameter match shown in Fig. 3(a). For example, the $|S_{11}|$ response of the Ladbrooke model at 11GHz in Fig. 3(a) is $|S_{11}| = 0.7856$, while $|S_{11}|$ from the measurement in Fig. 3 at the same frequency is $|S_{11}| = 0.7727$. In other words, the error in the mean value estimate is largely due to the deficiency of the model in matching the measurements of individual devices. Such deficiency can be viewed as a *deterministic* factor resulting in a deterministic shift in the estimated mean value. If adjusted for such a shift, the discrepancies in the mean values estimated by the Ladbrooke model would be reduced.

We also plot histograms of one S parameter as shown in Fig. 4, to further explore the validity of the models as suggested in [3]. It is very interesting to see that the Ladbrooke model closely reproduces the distribution pattern (spread) of the S parameters.



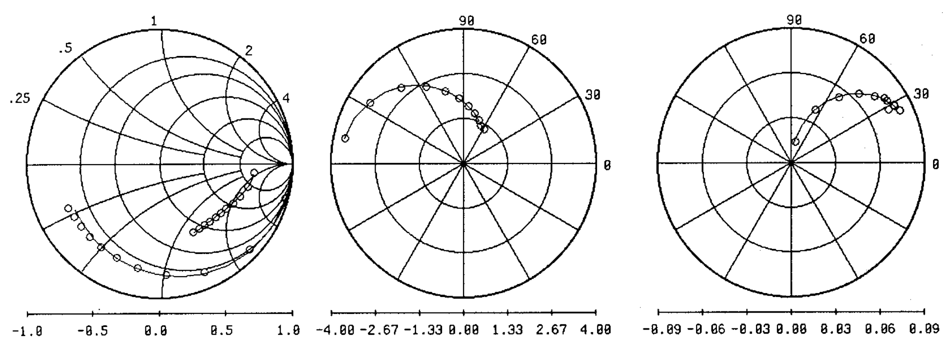
L_{g0} (a) I_{DSS} (b)

Fig. 2 Model parameter histograms. (a) Gate length L_{g0} in the Ladbrooke model. (b) I_{DSS} in the Materka and Kacprzak model.



S_{11} and S_{22} S_{21} S_{12}

(a)



S_{11} and S_{22} S_{21} S_{12}

(b)

Fig. 3 S-parameter fit. Circles represent the mean-valued S parameters at bias V_{GS}=0V and V_{DS}=5V. Solid lines are model responses simulated from the mean parameter values. (a) Fit by the Ladbrooke model. (b) Fit by the Materka and Kacprzak model.

TABLE II

MEAN VALUES AND STANDARD DEVIATIONS OF MEASURED AND SIMULATED S PARAMETERS AT 11GHZ

	Measured S Parameters		Simulated S Parameters			
			Ladbrooke Model		Materka and Kacprzak Model	
	Mean	Dev.(%)	Mean	Dev.(%)	Mean	Dev.(%)
$\lvert S_{11} \rvert$	0.773	.988	.7856	.764	.7725	1.74
$\angle S_{11}$	−114.3	1.36	−119.3	1.10	−114.9	1.63
$\lvert S_{21} \rvert$	1.919	.802	1.679	1.34	1.933	15.2
$\angle S_{21}$	93.35	.856	94.06	.835	93.43	.860
$\lvert S_{12} \rvert$	.0765	3.77	.07542	3.68	.07564	5.07
$\angle S_{12}$	34.00	2.51	31.98	2.33	33.72	2.14
$\lvert S_{22} \rvert$	0.5957	1.48	.5838	1.54	.5935	4.19
$\angle S_{22}$	−38.69	2.10	−36.86	1.42	−37.85	3.31

CONCLUSIONS

We have presented a case study, based on 69 devices, of statistical GaAs MESFET device modeling. We have shown that the Ladbrooke model based on physical parameters can preserve the statistical characteristics of the actual device. We could, therefore, use it in statistical circuit designs. We have also shown that the Materka equivalent circuit model can accurately fit the data from which the model parameters are extracted, because it has fewer constraints than the physical model.

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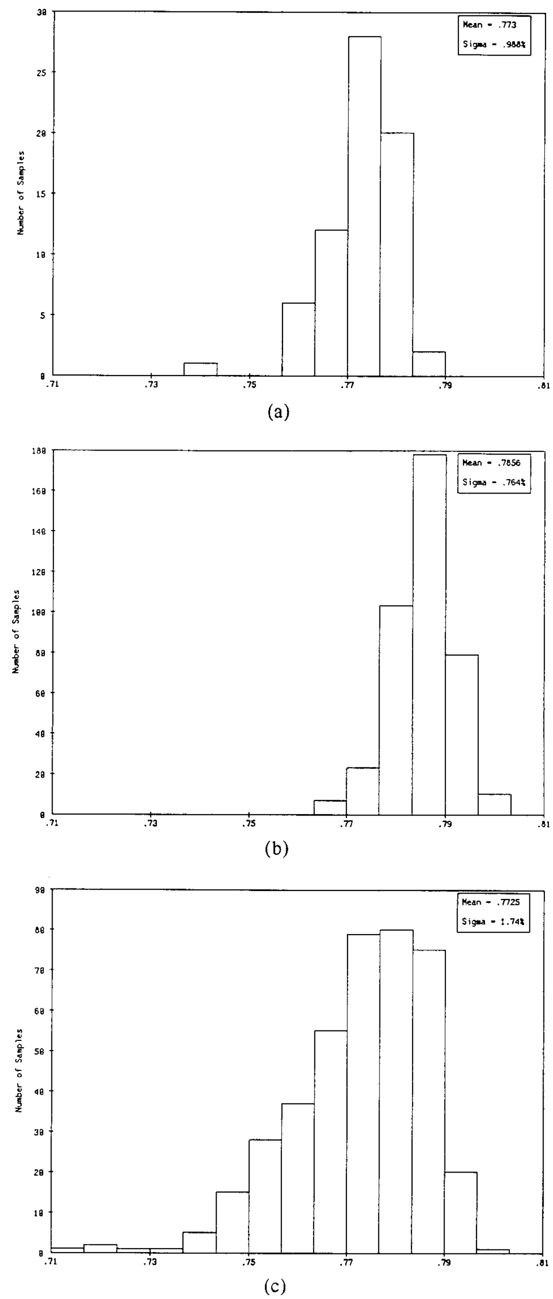

Fig. 4 Histograms of $|S_{11}|$ at V_{GS}=0V and V_{DS}=5V and at 11GHz from (a) measurements, (b) the Ladbrooke model, and (c) the Materka and Kacprzak model.