PhorsFET: A NEW PHYSICS-ORIENTED

STATISTICAL GaAs MESFET MODEL

OSA-91-MT-5-R

December 2, 1991

PhorsFET: A NEW PHYSICS-ORIENTED STATISTICAL GaAs MESFET MODEL

J.W. Bandler*, R.M. Biernacki*, Q. Cai*, S.H. Chen* and S. Ye

Optimization Systems Associates Inc.
P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7

Tel 416 628 8228
Fax 416 628 8225

Abstract

We present PhorsFET: a new physics-oriented statistical GaAs MESFET model. PhorsFET exploits the DC Khatibzadeh and Trew characterization and the small-signal Ladbrooke formulas. Statistical extraction and postprocessing of device physical parameters are carried out by HarPE™. Accuracy is demonstrated by good agreement between Monte Carlo simulations and the statistical data.

---

* J.W. Bandler, R.M. Biernacki and S.H. Chen are also with and Q. Cai is with the Simulation Optimization Systems Research Laboratory, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada L8S 4L7.

Manuscript submitted December 2, 1991.

SUMMARY

Introduction

Fabricated device parameter values deviate randomly from their nominal (or designed) values. These random variations result in complicated distributions and correlations of device responses, and directly affect production yield. Statistical modeling is needed to characterize the device statistics to provide accurate models for statistical analysis and yield optimization. Purviance *et al.* [1-3] studied some statistical properties of FETs based on equivalent circuit models (ECMs). Bandler *et al.* [4] investigated statistical modeling of GaAs MESFETs using both ECMs and physics-based models (PBMs). Using the Ladbrooke model [5], they demonstrated that PBMs provide more reliable estimates of device statistics than ECMs.

We have created PhorsFET (physics-oriented statistical GaAs MESFET), a new PBM, which exploits the DC Khatibzadeh and Trew characterization [6] and the small-signal Ladbrooke formulas. PhorsFET retains the advantages of the Ladbrooke model and the Khatibzadeh and Trew model while overcoming their respective shortcomings: the DC operating point for implementation of the Ladbrooke formulas has to be obtained separately; the Khatibzadeh and Trew model, while capable of DC simulation, seems to be inaccurate for small-signal statistical applications. The DC device simulation follows our improved version of the Khatibzadeh and Trew approach implemented in HarPE™ [7]. Then, the small-signal intrinsic parameters are derived using the Ladbrooke formulas with our modifications [4].

The new model is implemented in the statistical environment of HarPE [7], which carried out all the calculations we report here. The GaAs MESFET wafer measurements were provided by Plessey Research Caswell [8]. To align the measured data to consistent bias points, we applied the Materka and Kacprzak model [9] for accurate interpolation for individual devices.

Model accuracy is demonstrated by good agreement between Monte Carlo S-parameter simulations and the statistical S-parameter data. Furthermore, PhorsFET provides reliable and predictable results in yield optimization [10].

The PhorsFET Model for GaAs MESFETs

The small-signal equivalent circuit of the PhorsFET model based on Ladbrooke [5] is shown in Fig. 1. It includes parameters derived from device physical/geometrical parameters and the intrinsic voltages at the DC operating point. The attractive statistical properties of this model have been demonstrated in [4]. The DC operating point needed is solved for using the Khatibzadeh and Trew approach which we have improved for better efficiency for uniform doping and implemented in HarPE [7].

Details of the Khatibzadeh and Trew approach and the Ladbrooke formulas can be found in [4], [5], [7] and [9]. Our new model PhorsFET includes the intrinsic FET parameters

$$\{L, Z, a, N_d, V_{b0}, v_{sat}, E_c, \mu_0, \varepsilon, L_{G0}, a_0, r_{01}, r_{02}, r_{03}\} \tag{1}$$

and the linear extrinsic elements

$$\{L_g, R_g, L_d, R_d, L_s, R_s, G_{ds}, C_{ds}, C_{ge}, C_{de}\} \tag{2}$$

where L is the gate length, Z the gate width, a the channel thickness, N_d the doping density, V_{b0} the zero-bias barrier potential, v_{sat} the saturation value of electron drift velocity, E_c the critical electric field, μ_0 the low-field mobility of GaAs, ε the dielectric constant, L_{g0} the inductance from gate bond wires and pads, a_0 the proportionality coefficient, and r_{01}, r_{02} and r_{03} are fitting coefficients. The DC block capacitor C_x in Fig. 1 is fixed at 2pF.

The bias-dependent small-signal parameters, namely, g_m, C_{gs}, C_{gd}, R_i, L_g, r_0 and τ, as shown in Fig. 1, are derived using the modified Ladbrooke formulas once the DC operating point is solved for. For instance,

$$\begin{aligned} g_m &= \varepsilon v_{sat} Z/d \\ \tau &= (0.5X - 2d)L/(v_{sat}(L+2X)) \\ R_i &= LZ/(\mu_0 q N_d(a-d)) \\ C_{gd} &= 2\varepsilon Z/(1+2X/L) \\ r_0 &= r_{01} V_{D'S'}(r_{03} - V_{G'S'}) + r_{02} \end{aligned} \tag{3}$$

where $V_{D'S'}$ and $V_{G'S'}$ are DC intrinsic voltages from *D'* to *S'* and from *G'* to *S'*, respectively, as shown in Fig. 1. The equivalent depletion depth d and the space-charge layer extension X are defined by

$$d = [2\varepsilon(-V_{G'S'}+V_{b0})/(qN_d)]^{0.5}$$
$$X = a_0\{2\varepsilon/[qN_d(-V_{G'S'}+V_{b0})]\}^{0.5}(-V_{D'G'}+V_{b0}) \qquad (4)$$

Then PhorsFET is ready for small-signal simulation.

Measurement Data Interpolation

Measurements on 0.5μm GaAs MESFETs were provided by Plessey Research Caswell [8]. 69 individual devices (data sets) from two wafers are chosen for statistical modeling. Each data set contains small-signal S parameters measured at frequencies from 1GHz to 21GHz with 0.4GHz step and under three bias conditions (V_{DS} at 5V and V_{GS} approximately at 0V, -0.7V and -1.4V, respectively). DC drain bias currents are also included in the measurements.

The measurement bias conditions vary slightly from device to device, thus we need to align the different data sets to provide consistent bias points for statistical modeling. It is also desirable to interpolate measured data at other bias points. The Materka and Kacprzak model is a suitable interpolator for this purpose, because of its excellent single device fitting accuracy for these devices.

For each individual device we fit the Materka and Kacprzak model to its corresponding data set. The resulting models are used to interpolate data for each device at two bias points (gate bias -0.5V and -0.7V, drain bias 5V). In this way we generated data sets for 69 devices including DC responses and S parameters from 1GHz to 21GHz with 2GHz step under the two bias conditions.

Statistical Modeling and Verification

HarPE [7] represents model parameter statistics by mean values, standard deviations, correlation coefficients between model parameters and their discrete distribution functions (DDF) [11].

PhorsFET model parameters were extracted for each device by fitting the model responses to the corresponding S-parameter data and drain bias currents at gate bias -0.5V and -0.7V and drain bias 5V. The resulting 69 models were then postprocessed to obtain the parameter statistics (Table

I). Histograms of channel thickness and doping density are shown in Fig. 2.

For verification, 400 Monte Carlo outcomes were generated using PhorsFET. The statistics of the simulated S parameters for those 400 outcomes were compared with the statistics of the data. The mean values and standard deviations from the data and the simulated S parameters at both bias points and at frequency 11GHz are listed in Table II. Note that the statistics of the data and simulated S parameters are consistent. This validates the statistical properties of PhorsFET.

Conclusions

We have presented PhorsFET: a novel, accurate physics-oriented model for GaAs MESFETs, particularly suitable for statistical device characterization. Our experiments demonstrate its ability to accurately represent the statistical properties of MESFETs. PhorsFET has been implemented in HarPE and is suitable for both nominal design and yield optimization of small-signal circuits. Using PhorsFET, exciting results have been achieved in yield-driven amplifier design [10].

References

[1] J. Purviance, D. Criss and D. Monteith, "FET model statistics and their effects on design centering and yield prediction for microwave amplifiers," *IEEE Int. Microwave Symp. Dig.* (New York, NY), 1988, pp. 315-318.

[2] J.E. Purviance, M.C. Petzold and C. Potratz, "A linear statistical FET model using principal component analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 37, 1989, pp. 1389-1394.

[3] J. Purviance, M. Meehan and D. Collins, "Properties of FET parameter statistical data bases," *IEEE Int. Microwave Symp. Dig.* (Dallas, TX), 1990, pp. 567-570.

[4] J.W. Bandler, R.M. Biernacki, S.H. Chen, J. Song, S. Ye and Q.J. Zhang, "Statistical modeling of GaAs MESFETs," *IEEE Int. Microwave Symp. Dig.* (Boston, MA), 1991, pp. 87-90.

[5] P.H. Ladbrooke, *MMIC Design: GaAs FETs and HEMTs.* Norwood, MA: Artech House, 1989.

[6] M.A. Khatibzadeh and R.J. Trew, "A large-signal, analytic model for the GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 231-238.

[7] *HarPE*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1991.

[8] Measurement data provided by Plessey Research Caswell Ltd., Caswell, Towcester, Northamptonshire, England NN12 8EQ, 1990.

[9] A. Materka and T. Kacprzak, "Computer calculation of large-signal GaAs FET amplifier

characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, 1985, pp. 129-135.

[10] J.W. Bandler, S. Ye, Q. Cai, R.M. Biernacki and S.H. Chen, "Predictable yield-driven circuit optimization," submitted to 1992 *IEEE Int. Microwave Symp.*

[11] J.W. Bandler, R.M. Biernacki, S.H. Chen, J.F. Loman, M.L. Renault and Q.J. Zhang, "Combined discrete/normal statistical modeling of microwave devices," *Proc. 19th European Microwave Conf.* (London), 1989, pp.205-210.

TABLE I

PARAMETER STATISTICS OF PhorsFET

Para.	Mean	Dev.(%)	Para.	Mean	Dev.(%)
$L(\mu m)$	0.4997	4.76	$R_d(\Omega)$	0.4905	1.42
$a(\mu m)$	0.1630	5.78	$R_s(\Omega)$	3.9345	1.29
$N_d(m^{-3})$	2.475E23	4.21	$R_g(\Omega)$	7.7811	0.34
$V_{b0}(V)$	0.2661	34.6	$L_d(nH)$	6.21E-2	5.88
$L_{G0}(nH)$	0.0299	9.02	$L_s(nH)$	2.15E-2	7.31
$r_{01}(1/A^2)$	0.0779	0.17	$G_{ds}(1/\Omega)$	2.34E-3	4.19
$r_{02}(V)$	534.44	4.86	$C_{ds}(pF)$	5.89E-2	2.33
$r_{03}(\Omega)$	7.7855	0.17	$C_{ge}(pF)$	4.61E-2	6.12
			$C_{de}(pF)$	2.00E-4	0.05

TABLE II

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

	Bias 1				Bias 2			
	Data		PhorsFET		Data		PhorsFET	
	Mean	Dev.(%)	Mean	Dev.(%)	Mean	Dev.(%)	Mean	Dev.(%)
$\|S_{11}\|$	0.771	0.67	0.765	0.74	0.775	0.65	0.776	0.72
$\angle S_{11}$	-103.5	1.53	-104.2	1.62	-100.1	1.60	-100.5	1.54
$\|S_{21}\|$	1.760	2.26	1.707	2.84	1.657	3.23	1.668	2.78
$\angle S_{21}$	97.21	0.72	98.26	0.84	98.10	0.70	100.3	0.73
$\|S_{12}\|$	0.091	4.10	0.092	4.32	0.097	4.27	0.097	3.85
$\angle S_{12}$	35.59	1.74	35.04	2.13	36.20	1.63	35.45	2.12
$\|S_{22}\|$	0.576	1.57	0.577	1.66	0.577	1.78	0.579	1.66
$\angle S_{22}$	-39.48	1.42	-39.61	1.37	-39.96	1.26	-40.18	1.24

Bias 1: $V_{GS} = -0.5V$, $V_{DS} = 5V$. Bias 2: $V_{GS} = -0.7V$, $V_{DS} = 5V$.

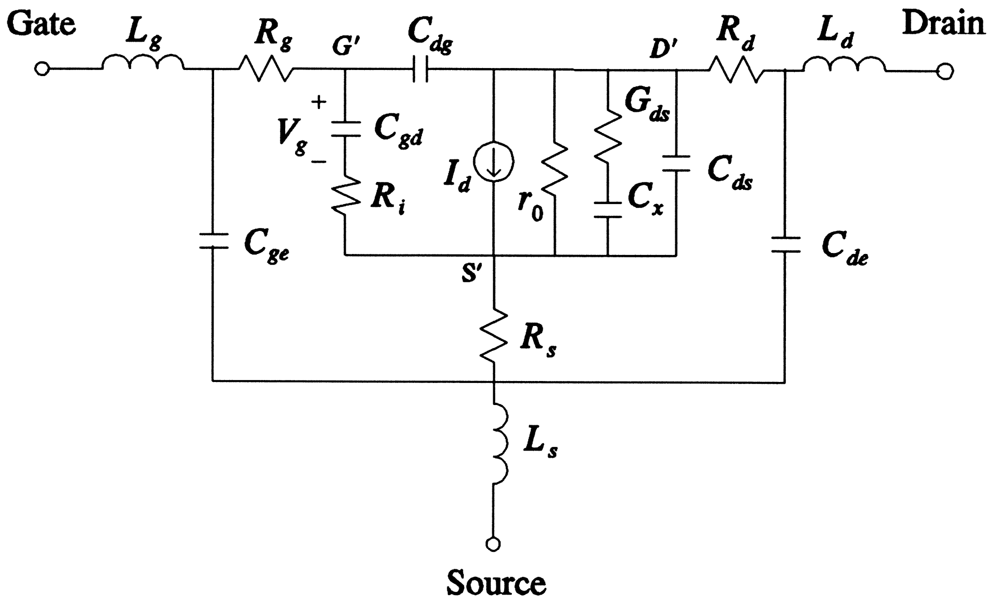
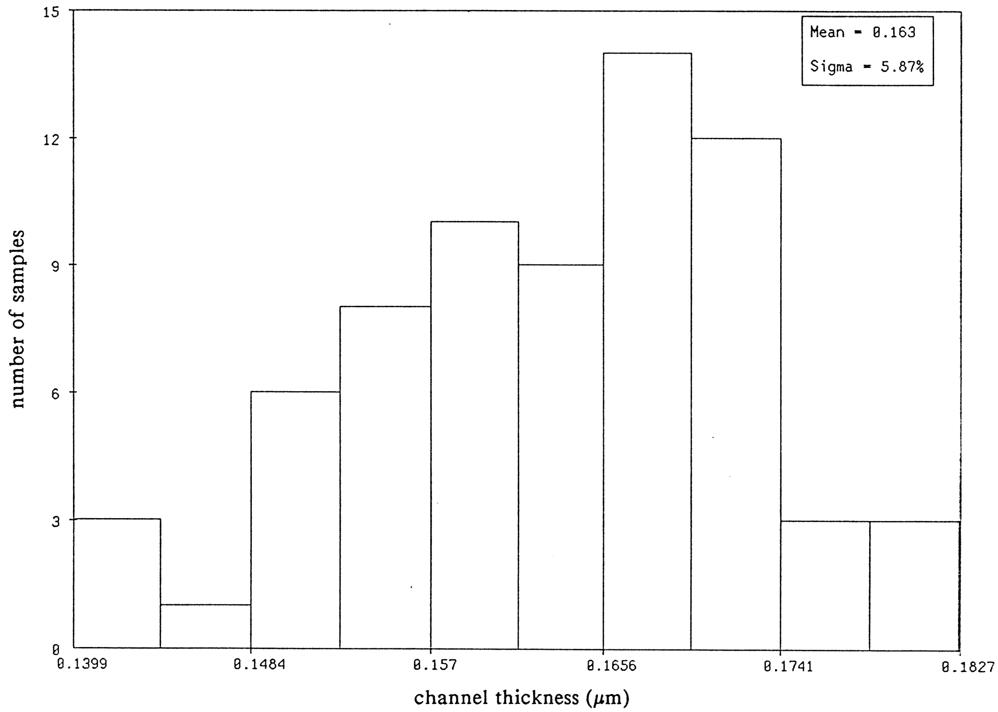
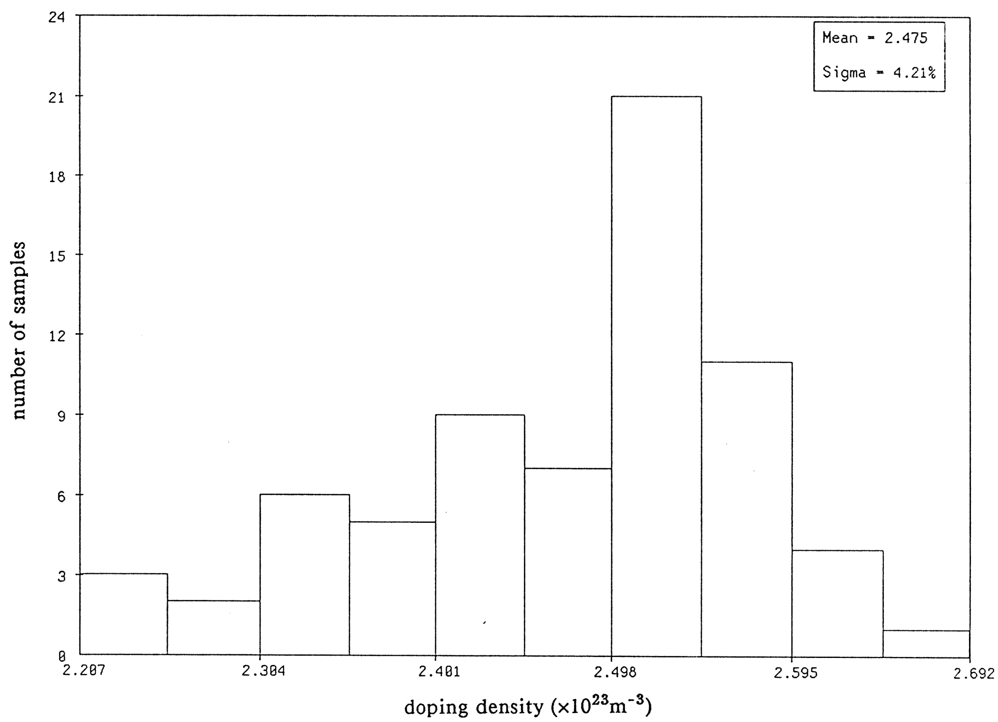


Fig. 1. Small-signal equivalent circuit where $I_d=g_mV_ge^{-j\omega\tau}$.



(a)



(b)

Fig. 2. Histograms of (a) channel thickness and (b) doping density.

PhorsFET: A NEW PHYSICS-ORIENTED STATISTICAL GaAs MESFET MODEL

J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and S. Ye

Optimization Systems Associates Inc.
P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7

Tel 416 628 8228
Fax 416 628 8225

Full Length

Topic Area: Nonlinear Modeling and Analysis

PhorsFET: A NEW PHYSICS-ORIENTED STATISTICAL GaAs MESFET MODEL

J.W. Bandler*, R.M. Biernacki*, Q. Cai*, S.H. Chen* and S. Ye

Optimization Systems Associates Inc.
P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7

Tel 416 628 8228
Fax 416 628 8225

Abstract

We present PhorsFET: a new physics-oriented statistical GaAs MESFET model. PhorsFET exploits the DC Khatibzadeh and Trew characterization and the small-signal Ladbrooke formulas. Statistical extraction and postprocessing of device physical parameters are carried out by HarPE™. Accuracy is demonstrated by good agreement between Monte Carlo simulations and the statistical data.

---

* J.W. Bandler, R.M. Biernacki and S.H. Chen are also with and Q. Cai is with the Simulation Optimization Systems Research Laboratory, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada L8S 4L7.

Manuscript submitted December 2, 1991.

SUMMARY

Introduction

Fabricated device parameter values deviate randomly from their nominal (or designed) values. These random variations result in complicated distributions and correlations of device responses, and directly affect production yield. Statistical modeling is needed to characterize the device statistics to provide accurate models for statistical analysis and yield optimization. Purviance *et al.* [1–3] studied some statistical properties of FETs based on equivalent circuit models (ECMs). Bandler *et al.* [4] investigated statistical modeling of GaAs MESFETs using both ECMs and physics–based models (PBMs). Using the Ladbrooke model [5], they demonstrated that PBMs provide more reliable estimates of device statistics than ECMs.

We have created PhorsFET (physics–oriented statistical GaAs MESFET), a new PBM, which exploits the DC Khatibzadeh and Trew characterization [6] and the small–signal Ladbrooke formulas. PhorsFET retains the advantages of the Ladbrooke model and the Khatibzadeh and Trew model while overcoming their respective shortcomings: the DC operating point for implementation of the Ladbrooke formulas has to be obtained separately; the Khatibzadeh and Trew model, while capable of DC simulation, seems to be inaccurate for small–signal statistical applications. The DC device simulation follows our improved version of the Khatibzadeh and Trew approach implemented in HarPE™ [7]. Then, the small–signal intrinsic parameters are derived using the Ladbrooke formulas with our modifications [4].

The new model is implemented in the statistical environment of HarPE [7], which carried out all the calculations we report here. The GaAs MESFET wafer measurements were provided by Plessey Research Caswell [8]. To align the measured data to consistent bias points, we applied the Materka and Kacprzak model [9] for accurate interpolation for individual devices.

Model accuracy is demonstrated by good agreement between Monte Carlo S–parameter simulations and the statistical S–parameter data. Furthermore, PhorsFET provides reliable and predictable results in yield optimization [10].

The PhorsFET Model for GaAs MESFETs

The small-signal equivalent circuit of the PhorsFET model based on Ladbrooke [5] is shown in Fig. 1. It includes parameters derived from device physical/geometrical parameters and the intrinsic voltages at the DC operating point. The attractive statistical properties of this model have been demonstrated in [4]. The DC operating point needed is solved for using the Khatibzadeh and Trew approach which we have improved for better efficiency for uniform doping and implemented in HarPE [7].

Details of the Khatibzadeh and Trew approach and the Ladbrooke formulas can be found in [4], [5], [7] and [9]. Our new model PhorsFET includes the intrinsic FET parameters

$$\{L, Z, a, N_d, V_{b0}, v_{sat}, E_c, \mu_0, \varepsilon, L_{G0}, a_0, r_{01}, r_{02}, r_{03}\} \tag{1}$$

and the linear extrinsic elements

$$\{L_g, R_g, L_d, R_d, L_s, R_s, G_{ds}, C_{ds}, C_{ge}, C_{de}\} \tag{2}$$

where L is the gate length, Z the gate width, a the channel thickness, N_d the doping density, V_{b0} the zero-bias barrier potential, v_{sat} the saturation value of electron drift velocity, E_c the critical electric field, μ_0 the low-field mobility of GaAs, ε the dielectric constant, L_{g0} the inductance from gate bond wires and pads, a_0 the proportionality coefficient, and r_{01}, r_{02} and r_{03} are fitting coefficients. The DC block capacitor C_x in Fig. 1 is fixed at 2pF.

The bias-dependent small-signal parameters, namely, g_m, C_{gs}, C_{gd}, R_i, L_g, r_0 and τ, as shown in Fig. 1, are derived using the modified Ladbrooke formulas once the DC operating point is solved for. For instance,

$$\begin{aligned} g_m &= \varepsilon v_{sat} Z/d \\ \tau &= (0.5X - 2d)L/(v_{sat}(L+2X)) \\ R_i &= LZ/(\mu_0 q N_d(a-d)) \\ C_{gd} &= 2\varepsilon Z/(1+2X/L) \\ r_0 &= r_{01} V_{D'S'}(r_{03} - V_{G'S'}) + r_{02} \end{aligned} \tag{3}$$

where $V_{D'S'}$ and $V_{G'S'}$ are DC intrinsic voltages from D' to S' and from G' to S', respectively, as shown in Fig. 1. The equivalent depletion depth d and the space-charge layer extension X are defined by

$$d = [2\varepsilon(-V_{G'S'}+V_{b0})/(qN_d)]^{0.5}$$
$$X = a_0\{2\varepsilon/[qN_d(-V_{G'S'}+V_{b0})]\}^{0.5}(-V_{D'G'}+V_{b0}) \quad (4)$$

Then PhorsFET is ready for small-signal simulation.

Measurement Data Interpolation

Measurements on 0.5μm GaAs MESFETs were provided by Plessey Research Caswell [8]. 69 individual devices (data sets) from two wafers are chosen for statistical modeling. Each data set contains small-signal S parameters measured at frequencies from 1GHz to 21GHz with 0.4GHz step and under three bias conditions (V_{DS} at 5V and V_{GS} approximately at 0V, -0.7V and -1.4V, respectively). DC drain bias currents are also included in the measurements.

The measurement bias conditions vary slightly from device to device, thus we need to align the different data sets to provide consistent bias points for statistical modeling. It is also desirable to interpolate measured data at other bias points. The Materka and Kacprzak model is a suitable interpolator for this purpose, because of its excellent single device fitting accuracy for these devices.

For each individual device we fit the Materka and Kacprzak model to its corresponding data set. The resulting models are used to interpolate data for each device at two bias points (gate bias -0.5V and -0.7V, drain bias 5V). In this way we generated data sets for 69 devices including DC responses and S parameters from 1GHz to 21GHz with 2GHz step under the two bias conditions.

Statistical Modeling and Verification

HarPE [7] represents model parameter statistics by mean values, standard deviations, correlation coefficients between model parameters and their discrete distribution functions (DDF) [11].

PhorsFET model parameters were extracted for each device by fitting the model responses to the corresponding S-parameter data and drain bias currents at gate bias -0.5V and -0.7V and drain bias 5V. The resulting 69 models were then postprocessed to obtain the parameter statistics (Table

I). Histograms of channel thickness and doping density are shown in Fig. 2.

For verification, 400 Monte Carlo outcomes were generated using PhorsFET. The statistics of the simulated S parameters for those 400 outcomes were compared with the statistics of the data. The mean values and standard deviations from the data and the simulated S parameters at both bias points and at frequency 11GHz are listed in Table II. Note that the statistics of the data and simulated S parameters are consistent. This validates the statistical properties of PhorsFET.

Conclusions

We have presented PhorsFET: a novel, accurate physics-oriented model for GaAs MESFETs, particularly suitable for statistical device characterization. Our experiments demonstrate its ability to accurately represent the statistical properties of MESFETs. PhorsFET has been implemented in HarPE and is suitable for both nominal design and yield optimization of small-signal circuits. Using PhorsFET, exciting results have been achieved in yield-driven amplifier design [10].

References

[1] J. Purviance, D. Criss and D. Monteith, "FET model statistics and their effects on design centering and yield prediction for microwave amplifiers," *IEEE Int. Microwave Symp. Dig.* (New York, NY), 1988, pp. 315-318.

[2] J.E. Purviance, M.C. Petzold and C. Potratz, "A linear statistical FET model using principal component analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 37, 1989, pp. 1389-1394.

[3] J. Purviance, M. Meehan and D. Collins, "Properties of FET parameter statistical data bases," *IEEE Int. Microwave Symp. Dig.* (Dallas, TX), 1990, pp. 567-570.

[4] J.W. Bandler, R.M. Biernacki, S.H. Chen, J. Song, S. Ye and Q.J. Zhang, "Statistical modeling of GaAs MESFETs," *IEEE Int. Microwave Symp. Dig.* (Boston, MA), 1991, pp. 87-90.

[5] P.H. Ladbrooke, *MMIC Design: GaAs FETs and HEMTs.* Norwood, MA: Artech House, 1989.

[6] M.A. Khatibzadeh and R.J. Trew, "A large-signal, analytic model for the GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 231-238.

[7] *HarPE*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1991.

[8] Measurement data provided by Plessey Research Caswell Ltd., Caswell, Towcester, Northamptonshire, England NN12 8EQ, 1990.

[9] A. Materka and T. Kacprzak, "Computer calculation of large-signal GaAs FET amplifier

characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, 1985, pp. 129-135.

[10] J.W. Bandler, S. Ye, Q. Cai, R.M. Biernacki and S.H. Chen, "Predictable yield-driven circuit optimization," submitted to 1992 *IEEE Int. Microwave Symp.*

[11] J.W. Bandler, R.M. Biernacki, S.H. Chen, J.F. Loman, M.L. Renault and Q.J. Zhang, "Combined discrete/normal statistical modeling of microwave devices," *Proc. 19th European Microwave Conf.* (London), 1989, pp.205-210.

TABLE I

PARAMETER STATISTICS OF PhorsFET

Para.	Mean	Dev.(%)	Para.	Mean	Dev.(%)
$L(\mu m)$	0.4997	4.76	$R_d(\Omega)$	0.4905	1.42
$a(\mu m)$	0.1630	5.78	$R_s(\Omega)$	3.9345	1.29
$N_d(m^{-3})$	2.475E23	4.21	$R_g(\Omega)$	7.7811	0.34
$V_{b0}(V)$	0.2661	34.6	$L_d(nH)$	6.21E−2	5.88
$L_{G0}(nH)$	0.0299	9.02	$L_s(nH)$	2.15E−2	7.31
$r_{01}(1/A^2)$	0.0779	0.17	$G_{ds}(1/\Omega)$	2.34E−3	4.19
$r_{02}(V)$	534.44	4.86	$C_{ds}(pF)$	5.89E−2	2.33
$r_{03}(\Omega)$	7.7855	0.17	$C_{ge}(pF)$	4.61E−2	6.12
			$C_{de}(pF)$	2.00E−4	0.05

TABLE II

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

	Bias 1				Bias 2			
	Data		PhorsFET		Data		PhorsFET	
	Mean	Dev.(%)	Mean	Dev.(%)	Mean	Dev.(%)	Mean	Dev.(%)
$\|S_{11}\|$	0.771	0.67	0.765	0.74	0.775	0.65	0.776	0.72
$\angle S_{11}$	−103.5	1.53	−104.2	1.62	−100.1	1.60	−100.5	1.54
$\|S_{21}\|$	1.760	2.26	1.707	2.84	1.657	3.23	1.668	2.78
$\angle S_{21}$	97.21	0.72	98.26	0.84	98.10	0.70	100.3	0.73
$\|S_{12}\|$	0.091	4.10	0.092	4.32	0.097	4.27	0.097	3.85
$\angle S_{12}$	35.59	1.74	35.04	2.13	36.20	1.63	35.45	2.12
$\|S_{22}\|$	0.576	1.57	0.577	1.66	0.577	1.78	0.579	1.66
$\angle S_{22}$	−39.48	1.42	−39.61	1.37	−39.96	1.26	−40.18	1.24

Bias 1: V_{GS} = −0.5V, V_{DS} = 5V. Bias 2: V_{GS} = −0.7V, V_{DS} = 5V.

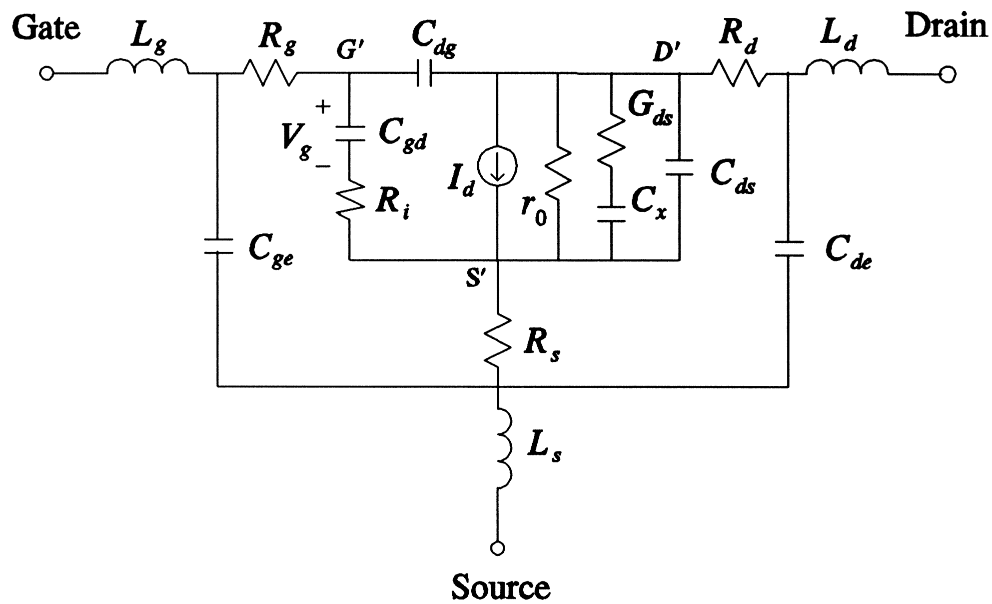


Fig. 1. Small-signal equivalent circuit where $I_d = g_m V_g e^{-j\omega\tau}$.

(a)

(b)

Fig. 2. Histograms of (a) channel thickness and (b) doping density.