A ROBUST PHYSICS-ORIENTED
STATISTICAL GaAs MESFET MODEL

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Introduction

random variations in the manufacturing environment result in complicated distributions and correlations of device responses

statistical modeling is a prerequisite for statistical analysis and yield optimization

statistical models:

- equivalent circuit models (ECMs)
- abstract models
- data bases
- physics-based models (PBMs)

a novel robust GaAs MESFET statistical PBM for small-signal applications which combines the advantages of the Khatibzadeh and Trew model and the Ladbrooke model (KTL) while overcoming their respective shortcomings

data alignment to adjust the measured data to meet the requirement of consistent measurement conditions for statistical modeling

multi-device parameter extraction and statistical postprocessing for statistical modeling

statistical model verification using Monte Carlo simulation

Abstract

We present a robust physics-oriented statistical GaAs MESFET model. Our model integrates the DC Khatibzadeh and Trew model for DC simulation with the Ladbrooke formulas for small-signal analysis (KTL). Accuracy of the statistical KTL model is verified by Monte Carlo simulations using device measurements. Statistical extraction and postprocessing of device physical parameters are carried out by HarPE.

The KTL Model for GaAs MESFETs

the Ladbrooke model:

equivalent circuit model (ECM)
suitable for small-signal applications
elements values derived from physical parameters
attractive statistical properties
DC operating point must be determined separately

the Khatibzadeh and Trew model:

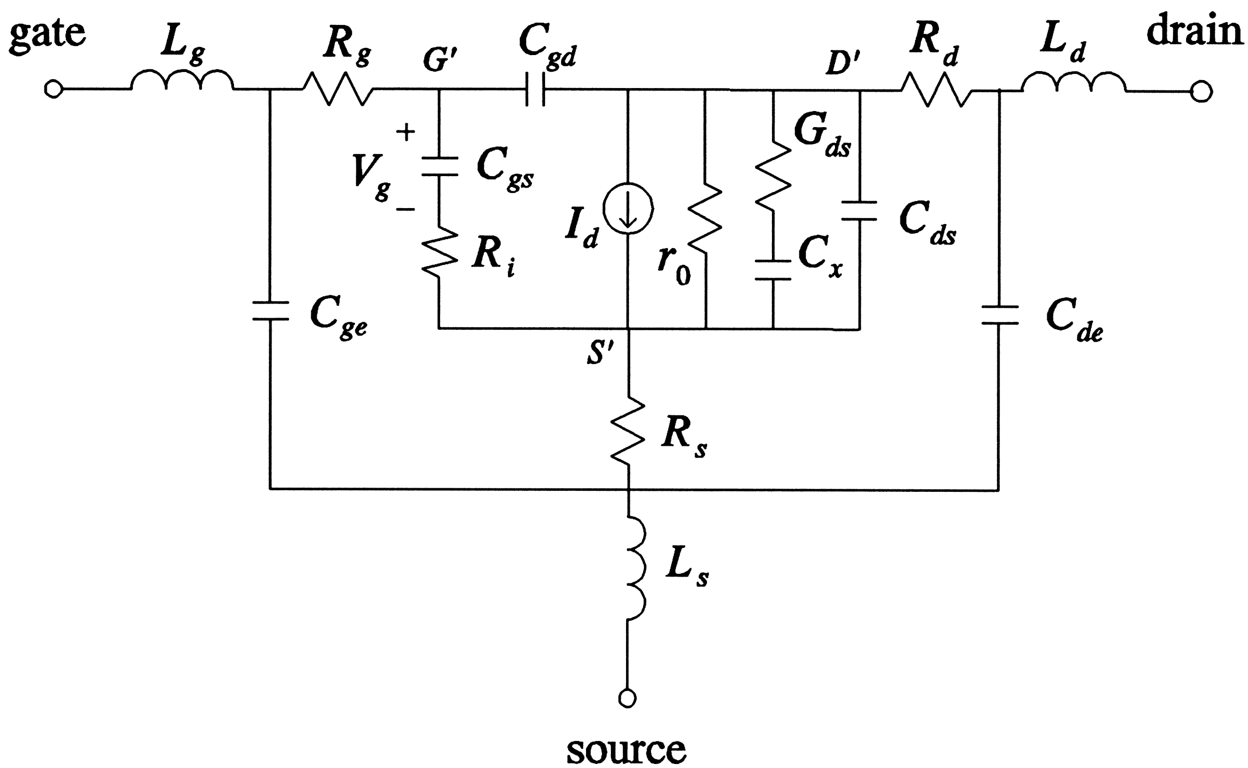
analytical physics-based model (PBM)
suitable for large-signal (or global) applications
capable of providing accurate DC solutions
not accurate enough for small-signal statistical modeling

the KTL model:

complete and accurate DC/small-signal modeling
the Ladbrooke model for small-signal simulation
the Khatibzadeh and Trew model for DC simulation
same physical parameters shared by both models
integrated and consistently defined statistical model

Small-Signal Equivalent Circuit

the KTL small-signal equivalent circuit follows the Ladbrooke model



the current I_d is calculated by

$$I_d = g_m V_g e^{-j\omega\tau}$$

g_m, C_{gs}, C_{gd}, R_i, L_g, r_0 and τ are bias-dependent parameters

Model Parameters

the model consists of intrinsic and extrinsic parameters including physical parameters, fitting coefficients and linear elements

intrinsic FET parameters:

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

extrinsic linear elements:

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

L, Z, a	gate length, gate width, channel thickness
N_d, V_{b0}	doping density, zero-bias barrier potential
v_{sat}	saturation electron drift velocity
μ_0, ε	low-field mobility, dielectric constant
L_{G0}	inductance from gate bond wires and pads
$a_0, r_{01}, r_{02}, r_{03}$	fitting coefficients

Model Equations

DC operating point is determined using the Khatibzadeh and Trew model

the bias-dependent small-signal parameters are then determined using the modified Ladbrooke formulas

$$g_m = \varepsilon v_{sat} Z/d$$

$$\tau = [0.5X - 2dL/(L+2X)]/v_{sat}$$

$$R_i = L/[Z\mu_0 q N_d(a-d)]$$

$$C_{gd} = 2\varepsilon Z/(1+2X/L)$$

$$r_0 = r_{01} V_{D'S'}(r_{02} - V_{G'S'}) + r_{03}$$

where $V_{D'S'}$ and $V_{G'S'}$ are DC intrinsic voltages, d and X are the equivalent depletion depth and the space-charge layer extension defined by

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

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

Measurement Data Alignment

statistical modeling requires data for different, but supposedly identical, devices to be taken under identical measurement conditions

the measurement conditions for different devices may not be identical due to the variations in measurement environment

measurement data need to be preprocessed to align data for statistical modeling

measurements on 0.5 μm GaAs MESFETs were chosen for statistical modeling from the Plessey data

34 individual devices from Wafer B and 35 individual devices from Wafer D with a variation of gate bias voltages of about 6 % (standard deviation)

the Materka and Kacprzak model was used for data alignment because of its excellent single device fitting accuracy for these devices

the data, aligned at two bias points (gate bias voltages -0.5 V and -0.7 V, drain bias voltage 5 V), include DC responses and *S* parameters from 1 GHz to 21 GHz with 2 GHz step

Statistical Modeling

our statistical modeling technique consists of two stages: multi-device parameter extraction and statistical postprocessing

multi-device parameter extraction:

> the KTL model parameters were extracted for each device by fitting the model responses to the corresponding S-parameter data and DC responses

statistical postprocessing:

> the deterministic models obtained by multi-device parameter extraction were postprocessed to obtain the parameter statistics

the resulting concise statistical model:

> the mean values, standard deviations, correlation matrix and discrete distribution functions (DDFs)

all the aforementioned processes were carried out by HarPE

TABLE I
KTL MODEL PARAMETERS FOR WAFER B

Parameter	Mean	Std. Dev. (%)
$L(\mu m)$	0.5237	2.84
$a(\mu m)$	0.1438	2.37
$N_d(m^{-3})$	2.1857×10^{23}	1.88
$v_{sat}(m/s)$	10.6416×10^{4}	2.85
$\mu_0(m^2/Vns)$	5.8309×10^{-10}	2.26
$L_{G0}(nH)$	0.0355	15.0
$r_{01}(\Omega/V^2)$	0.3525	0.277
$r_{02}(\Omega)$	2014.5	0.276
a_0	0.9978	1.19
$R_d(\Omega)$	1.0169	1.27
$R_s(\Omega)$	3.5209	3.46
$R_g(\Omega)$	6.5181	0.22
$L_d(nH)$	0.0766	9.58
$L_s(nH)$	0.0382	3.75
$G_{ds}(1/\Omega)$	3.7406×10^{-3}	1.63
$C_{ds}(pF)$	0.0505	1.57
$C_{ge}(pF)$	0.0669	5.84
$C_{de}(pF)$	0.0104	2.16
$C_x(pF)$	3.2699	1.69

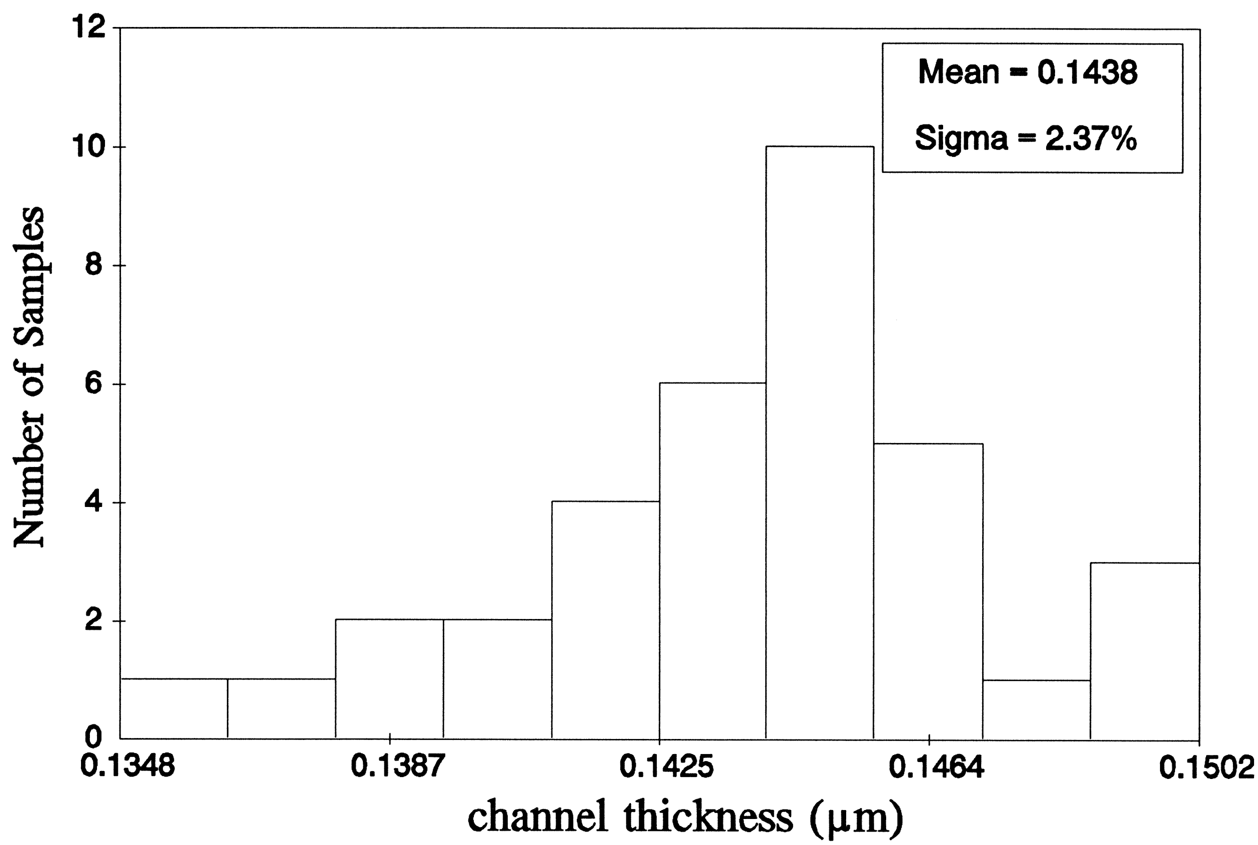
Z = 300 μm, ε =12.9, V_{b0} = 0.6 V and r_{03} = 7.0 V are fixed parameters. The bias-dependent linear extrinsic element L_g is computed using the Ladbrooke formula.

TABLE II
KTL MODEL PARAMETERS FOR WAFER D

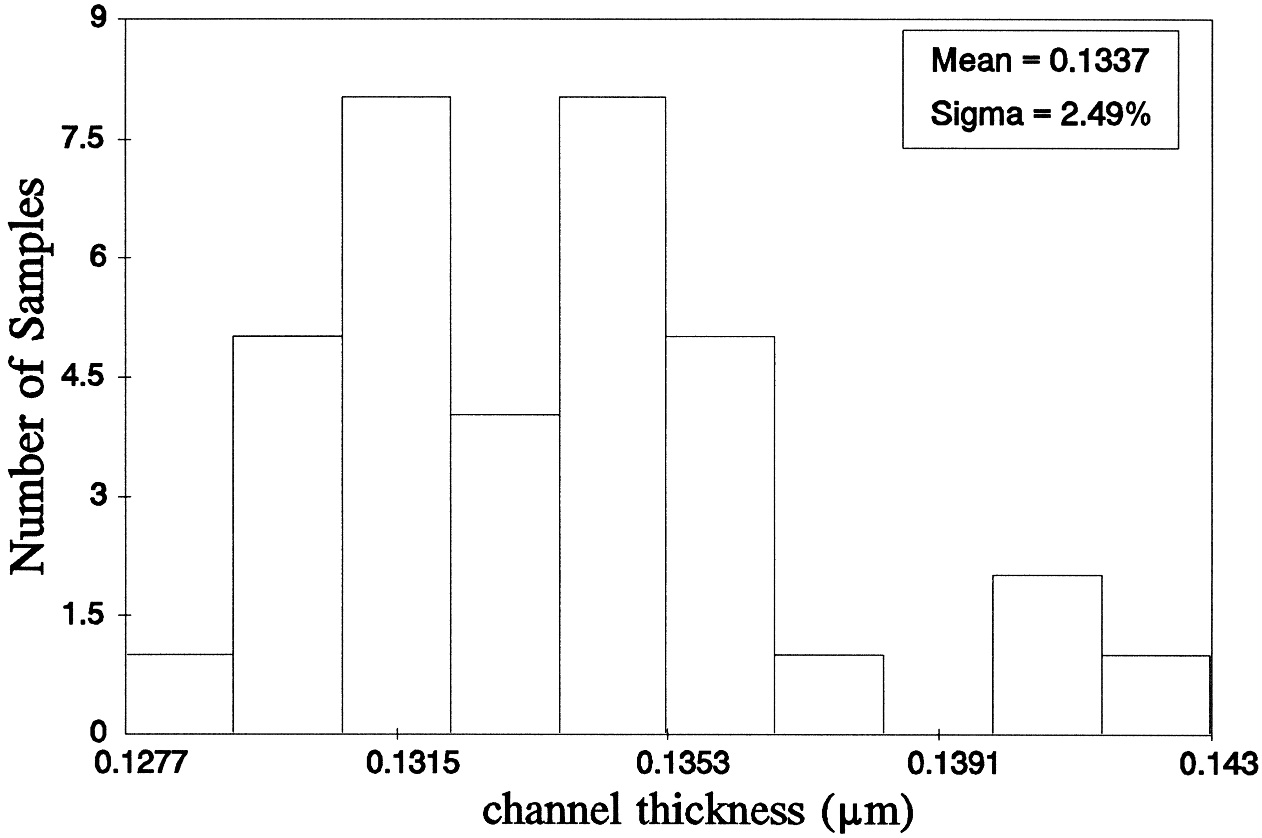
Parameter	Mean	Std. Dev. (%)
$L(\mu m)$	0.5055	3.93
$a(\mu m)$	0.1337	2.49
$N_d(m^{-3})$	2.2885×10^{23}	2.19
$v_{sat}(m/s)$	9.8251×10^{4}	5.22
$L_{G0}(nH)$	0.0375	15.4
$r_{01}(\Omega/V^2)$	0.3463	2.15
$r_{02}(\Omega)$	1979.0	2.15
a_0	0.9337	5.71
$R_d(\Omega)$	1.0416	1.70
$R_s(\Omega)$	3.8814	4.77
$R_g(\Omega)$	6.5256	0.41
$L_d(nH)$	0.0499	12.7
$L_s(nH)$	0.0359	8.10
$G_{ds}(1/\Omega)$	3.6315×10^{-3}	3.71
$C_{ds}(pF)$	0.0517	1.92
$C_{ge}(pF)$	0.0733	7.74
$C_{de}(pF)$	0.0106	2.75
$C_x(pF)$	3.7355	12.1

Z = 300 μm, ε = 12.9, V_{b0} = 0.6 V, r_{03} = 7.0 V and $\mu_0 = 6.0\times10^{-10}$ m^2/Vns are fixed parameters. The bias-dependent linear extrinsic element L_g is computed using the Ladbrooke formula.

Histogram of Channel Thickness for Wafer B



Histogram of Channel Thickness for Wafer D



Model Verification

for accurate statistical model the statistics of the simulated responses should match the statistics of the data

statistical model verification using Monte Carlo simulation

400 Monte Carlo outcomes were generated using the statistical KTL model

the statistics of the simulated *S* parameters and DC drain currents for those 400 outcomes were compared with the statistics of the data

the statistics of the data and the KTL model responses are consistent

TABLE III
MEAN VALUES AND STANDARD DEVIATIONS OF DATA AND KTL MODEL RESPONSES FOR WAFER B

	Bias 1				Bias 2			
	Data		KTL		Data		KTL	
	Mean	Dev. (%)	Mean	Dev. (%)	Mean	Dev. (%)	Mean	Dev. (%)
$\|S_{11}\|$	0.777	0.83	0.778	0.63	0.780	0.81	0.788	0.61
$\angle S_{11}$	-104.7	1.32	-105.8	1.00	-101.3	1.38	-102.7	1.07
$\|S_{21}\|$	1.793	1.17	1.739	1.44	1.703	1.61	1.700	1.47
$\angle S_{21}$	96.80	0.61	96.82	0.56	97.78	0.60	98.54	0.57
$\|S_{12}\|$	0.090	2.46	0.092	1.28	0.095	2.49	0.096	1.22
$\angle S_{12}$	35.30	1.35	35.64	1.58	35.95	1.30	34.80	1.59
$\|S_{22}\|$	0.571	0.90	0.574	0.72	0.572	0.91	0.576	0.71
$\angle S_{22}$	-39.58	1.23	-40.0	1.21	-39.91	1.21	-40.53	1.20
I_d(A)	0.040	8.16	0.039	7.71	0.033	9.51	0.033	8.76

Bias 1: V_{GS} = -0.5 V, V_{DS} = 5 V.
Bias 2: V_{GS} = -0.7 V, V_{DS} = 5 V.
Frequency is 11 GHz for S parameters.

TABLE IV
MEAN VALUES AND STANDARD DEVIATIONS OF DATA AND KTL MODEL RESPONSES FOR WAFER D

	Bias 1				Bias 2			
	Data		KTL		Data		KTL	
	Mean	Dev. (%)	Mean	Dev. (%)	Mean	Dev. (%)	Mean	Dev. (%)
$\lvert S_{11} \rvert$	0.784	0.44	0.785	0.59	0.787	0.45	0.794	0.59
$\angle S_{11}$	-103.9	2.24	-105.8	1.81	-100.4	2.37	-102.7	1.91
$\lvert S_{21} \rvert$	1.725	2.14	1.648	2.88	1.612	3.0	1.608	2.95
$\angle S_{21}$	97.06	0.99	96.96	0.82	97.91	0.94	98.69	0.84
$\lvert S_{12} \rvert$	0.096	3.35	0.095	3.11	0.102	3.45	0.100	3.07
$\angle S_{12}$	34.51	1.78	33.97	1.99	35.25	1.76	34.19	2.08
$\lvert S_{22} \rvert$	0.583	1.18	0.591	1.01	0.588	1.09	0.593	1.00
$\angle S_{22}$	-40.51	0.97	-40.40	0.92	-40.47	0.84	-40.88	0.92
I_d(A)	0.031	9.54	0.031	9.73	0.025	11.2	0.025	11.0

Bias 1: V_{GS} = -0.5 V, V_{DS} = 5 V.
Bias 2: V_{GS} = -0.7 V, V_{DS} = 5 V.
Frequency is 11 GHz for S parameters.

Conclusions

we have presented the KTL model: a physics-oriented model for GaAs MESFETs particularly suitable for small-signal statistical device characterization

our experiments demonstrate its ability to accurately represent the statistical properties of MESFETs

we have described data interpolation to align the measurement data to identical conditions for statistical modeling

the statistical KTL model was verified using Monte Carlo simulation

KTL has been implemented in HarPE and OSA90/hope and is suitable for both nominal design and yield optimization of small-signal circuits

using KTL, exciting results have been achieved in yield optimization

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