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OSA-93-OS-16-R

October 13, 1993

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Abstract

In this paper 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 measurement data. Statistical extraction and postprocessing of device physical parameters are carried out by HarPE.

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Manuscript submitted October 15, 1993.

SUMMARY

Introduction

In IC manufacturing 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 affect production yield. Statistical modeling is needed to characterize the device statistics to provide accurate response prediction for statistical analysis and yield optimization.

Statistical models can be based on equivalent circuit models (ECMs), abstract models, data bases and physics-based models (PBMs). The advantages of PBMs for statistical modeling and yield optimization have been discussed by a number of researchers, e.g., [1-7]. The Ladbrooke model [8], in particular, has been used by Bandler *et al.* [1-3] and by Bastida *et al.* [6] for GaAs MESFET statistical modeling and yield optimization. Very promising results have been reported.

In this paper we present a novel robust GaAs MESFET statistical PBM for small-signal applications which we call the KTL (Khatibzadeh/Trew/Ladbrooke) statistical model. It combines the advantages of the Khatibzadeh and Trew model [9] and the small-signal Ladbrooke model [8] while overcoming their respective shortcomings. The KTL model has been implemented in the flexible statistical environment of HarPE [10] and OSA90/hope [11].

We also discuss the concept of data alignment to adjust the measured data to meet the requirement of consistent measurement conditions for statistical modeling. Deterministic models are extracted for individual manufactured outcomes from the corresponding measured data. These models are used to generate "pseudo measurements" at some other bias conditions. We apply the Materka and Kacprzak model [12] to this end.

Using HarPE [10] we illustrate the benefit of the KTL model by statistical characterization of a GaAs MESFET from wafer measurements [13]. Model accuracy is demonstrated by good agreement between Monte Carlo simulations using the KTL model and the statistical data.

The KTL Model for GaAs MESFETs

The Ladbrooke model [8] is a small-signal model which includes element values derived from device physical/geometrical parameters and intrinsic voltages at the DC operating point. Its attractive statistical properties have already been noticed in [1,2,6]. However, the intrinsic voltages at the DC operating point must be determined separately.

On the other hand the Khatibzadeh and Trew model [9] is a large-signal (or global) model which is capable of providing accurate DC solutions. However, for small-signal applications, in particular statistical modeling, it is not as accurate as the Ladbrooke model [2].

For complete and accurate DC/small-signal device simulations we created the KTL model by combining the Ladbrooke model with the Khatibzadeh and Trew model. The latter is employed to solve for the DC operating point needed in establishing the former. Both models share the same physical parameters, therefore the resulting combined, or integrated, model is consistently defined.

The KTL small-signal equivalent circuit follows the Ladbrooke model and is shown in Fig. 1. The model 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 [1].

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,

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

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

$$R_i = L/(Z\mu_0 q N_d(a-d)), \tag{3}$$

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

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

where $V_{D'S'}$ and $V_{G'S'}$ are DC intrinsic voltages 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

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

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

Measurement Data Alignment

Statistical modeling requires data for different, but supposedly identical, devices to be taken under identical measurement conditions. However, the measurement conditions (e.g., the bias conditions) of different devices may not be identical. We preprocess the data to achieve bias condition alignment.

Measurements on 0.5μm GaAs MESFETs were provided by Plessey Research Caswell [13]. There were 41 devices (data sets) from Wafer B and 39 devices from Wafer D. Each data set contains small-signal S parameters measured at frequencies from 1GHz to 21GHz with 0.4GHz step under three bias conditions with a fixed drain bias V_{DS} = 5V. DC drain bias currents are also included in the measurements. We eliminated the "wild" devices (due to the measurement error) and selected 34 individual devices from Wafer B and 35 individual devices from Wafer D for statistical modeling. A robust approach using Huber optimization [14] to automatically eliminate wild devices is being developed.

Due to the variations of the measurement conditions the gate bias voltages vary slightly from device to device except for V_{GS} = 0V. For Wafer B V_{GS} of another two bias conditions varies between -0.79V and -0.59V (mean value -0.6818V and standard deviation 6.73%) and between -1.38V and -1.09V (mean values -1.232V and standard deviation 6.07%), respectively. For Wafer

D V_{GS} of another two bias conditions varies between -0.89V and -0.74V (mean values -0.8039V and standard deviation 5.83%) and between -1.64V and -1.25V (mean values -1.347V and standard deviation 5.93%), respectively. Therefore, 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 fitted the Materka and Kacprzak model to its corresponding data set. The resulting models were used to interpolate data for each device at two bias points (gate bias voltages -0.5V and -0.7V, drain bias voltage 5V). In this way we generated 34 data sets for Wafer B and 35 data sets for Wafer D including DC responses and S parameters from 1GHz to 21GHz with 2GHz step under the two bias conditions.

Statistical Modeling and Verification

Our statistical modeling technique consists of two stages: multi-device parameter extraction and postprocessing. The two stages, leading to a concise model described by the means, standard deviations, correlation matrix and discrete distribution functions (DDFs), were carried out by HarPE [10]. After alignment of the measurement data described in the preceding section, the KTL 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 34 (deterministic) models of Wafer B and the 35 models of Wafer D were then postprocessed to obtain the parameter statistics, respectively. The resulting mean values and the standard deviations for Wafer B and Wafer D are listed in Table I and Table II, respectively. Histograms of channel thickness and doping density for Wafer B and Wafer D are shown in Fig. 2 and Fig. 3, respectively.

For verification, 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 mean values and standard deviations from the data and the KTL model responses including S parameters at frequency 11GHz as well as the DC drain currents at both bias points for Wafer B and Wafer D are listed in Table III and Table IV, respectively. Note that the statistics of the data and the KTL model responses are consistent.

Conclusions

We have presented the KTL model: a physics-oriented model for GaAs MESFETs particularly suitable for robust statistical device characterization. Our experiments demonstrate its ability to accurately represent the statistical properties of MESFETs. 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-driven amplifier design [3].

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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
$Z(\mu m)$	300	*
ε	12.9	*
$V_{b0}(V)$	0.6	*
$r_{03}(V)$	7.0	*

* Assumed fixed (non-statistical) parameters.
The bias-dependent linear extrinsic element L_g is computed using the Ladbrooke formula [8].

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
$Z(\mu m)$	300	*
ε	12.9	*
$V_{b0}(V)$	0.6	*
$r_{03}(\Omega)$	7.0	*
$\mu_0(m^2/Vns)$	6.0×10^{-10}	*

* Assumed fixed (non-statistical) parameters.
The bias-dependent linear extrinsic element L_g is computed using the Ladbrooke formula [8].

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	-40.03	1.21	-39.91	1.21	-40.53	1.20
I_d(A)	0.040	8.16	0.0398	7.71	0.033	9.51	0.033	8.76

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

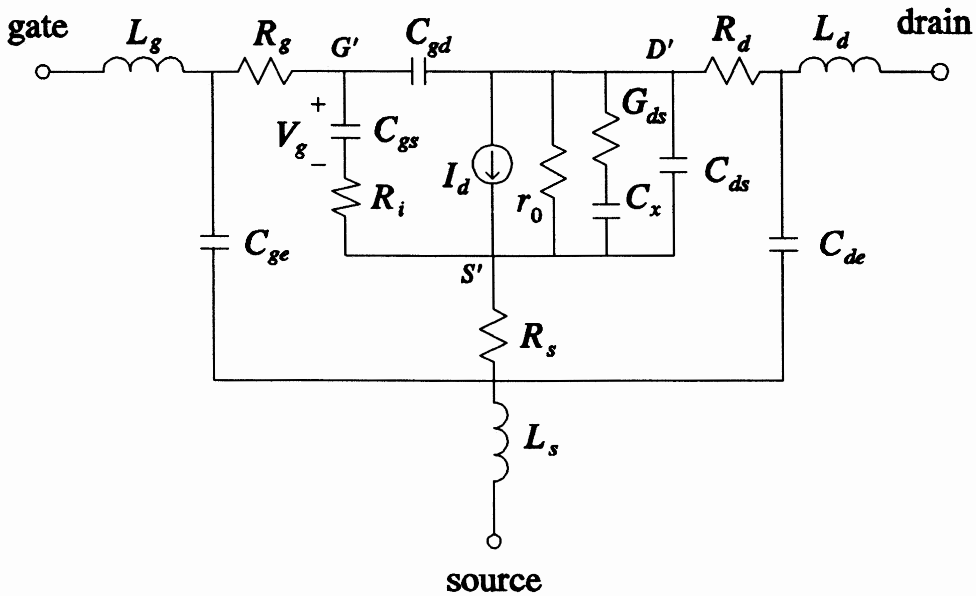
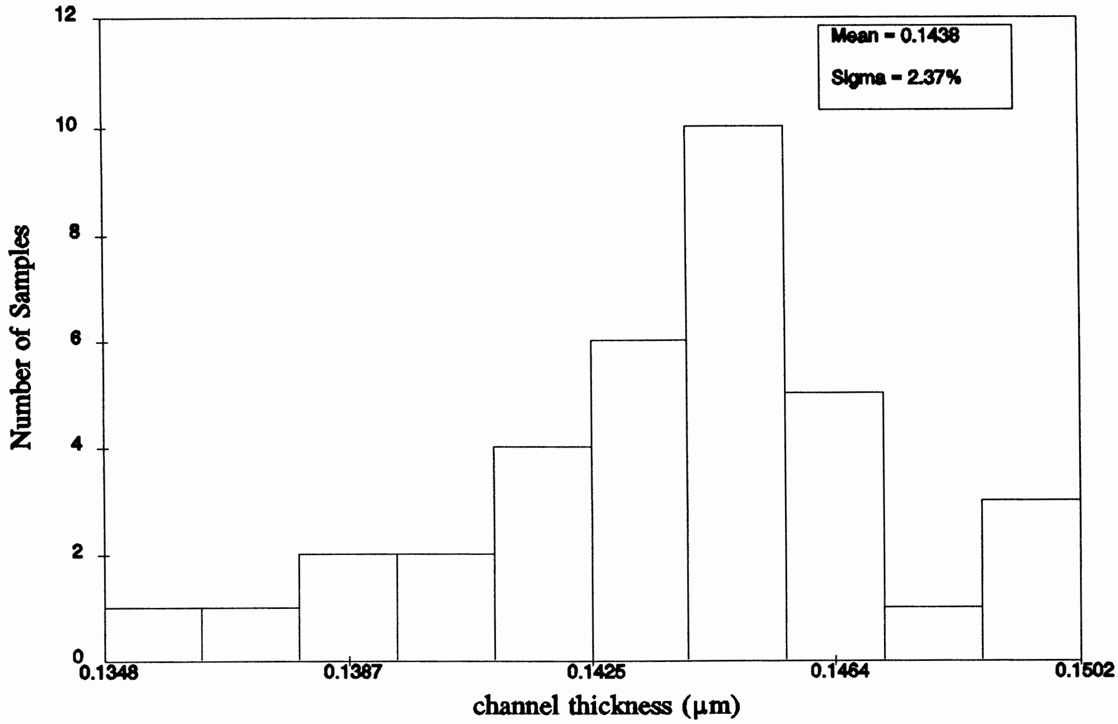
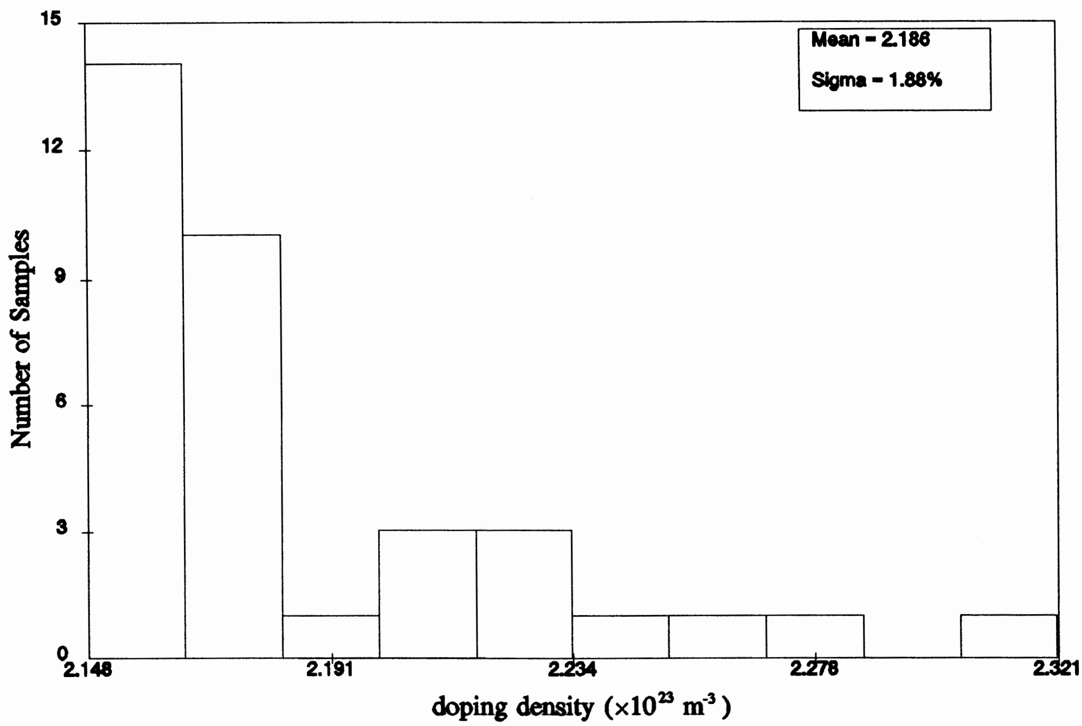


Fig. 1 Small-signal equivalent circuit where $I_d = g_m V_g e^{-j\omega\tau}$.

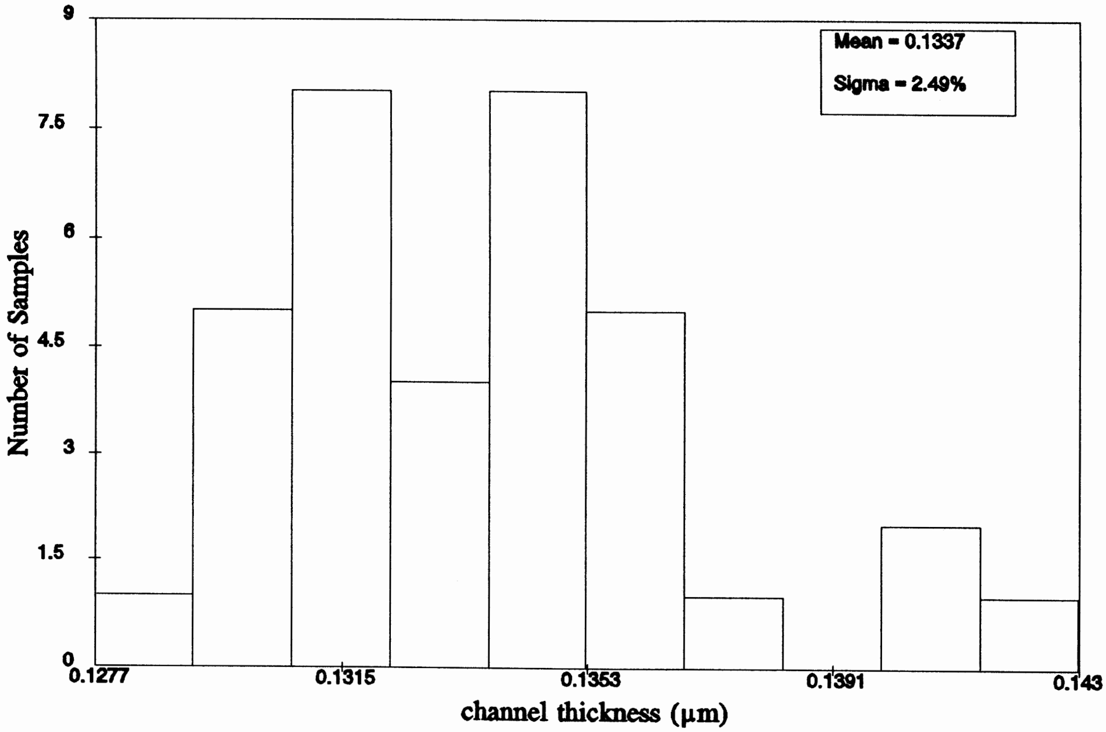


(a)



(b)

Fig. 2 Histograms of (a) channel thickness and (b) doping density for Wafer B obtained from statistical postprocessing of extracted parameters.



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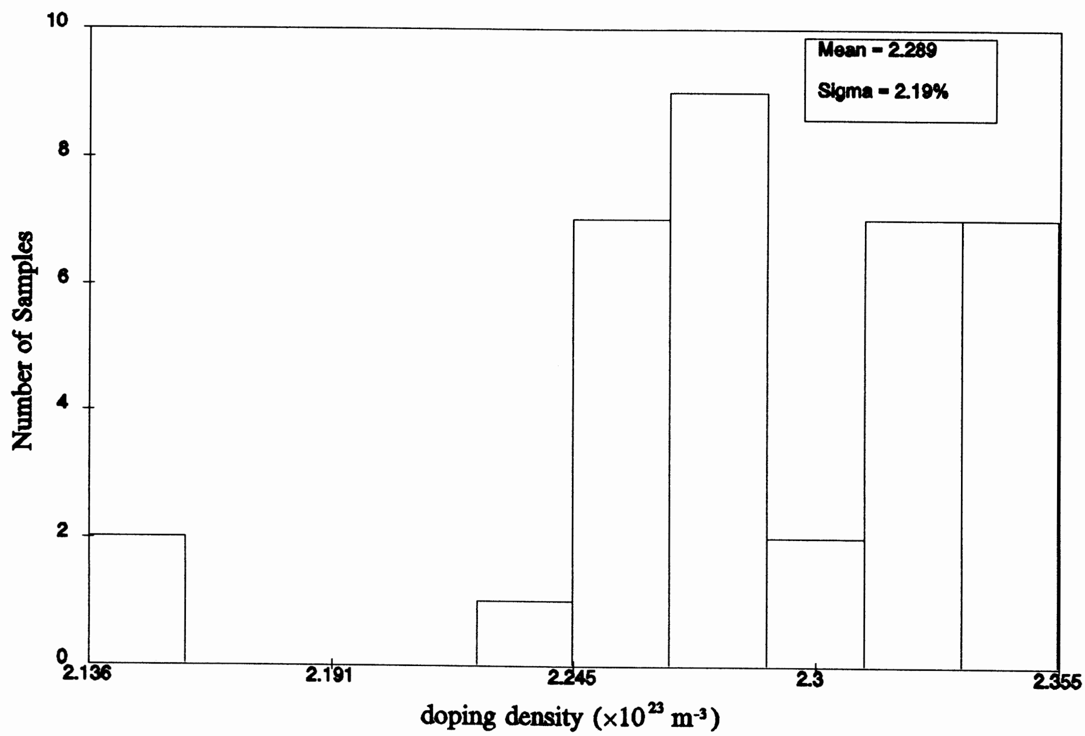

(b)

Fig. 3 Histograms of (a) channel thickness and (b) doping density for Wafer D obtained from statistical postprocessing of extracted parameters.