FET MODEL STATISTICS AND THEIR EFFECTS ON DESIGN CENTERING AND YIELD PREDICTION FOR MICROWAVE AMPLIFIERS

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ABSTRACT

The first and second order statistics for the model parameters of a TriQuint 0.5 um GaAs FET are determined and then tested in a statistical circuit design and yield simulation. The purpose is to identify what statistical FET data is needed to statistically design a high yield MMIC amplifier. An example is used to identify which aspects of statistical circuit design are sensitive to the proper FET model statistics. It is shown that the design values are insensitive and the yield estimates are sensitive. The important issues in statistical circuit design are summarized and a discussion of the needed future works is given.

INTRODUCTION

The manufacturing environment for microwave amplifiers is not fixed, but random, which results in random variations in the components of the manufactured amplifier. However most amplifier design is accomplished by optimization at the nominal parameter values only. This can result in an amplifier which performs poorly during manufacture. Using statistical circuit design, the random component variations expected during manufacture are taken into account by the design engineer, resulting is an amplifier where the manufacturing yield has been optimized rather than the nominal performance. Many papers have shown that significant increases in manufacturing yield can be obtained when statistical rather than nominal design is accomplished [2,3, for example]. Statistical circuit design is very important for the manufacture of high yield monolithic microwave integrated circuits (MMIC's), where circuit parameter values are especially difficult to control.
Before statistical circuit design can be fully used in the industry, there are several areas that need to be further addressed. These include:

- fast and accurate algorithms for yield estimation,
- yield optimization techniques,
- identification of the important statistical properties of the manufacturing process.

This paper addresses the last of these areas. The GaAS FET is the most variable element in a GaAs MMIC [4] and its statistics are studied here. The purpose is to identify which aspects of statistical circuit design are sensitive to the assumptions made about the FET model parameter statistics.

FET MODEL AND DATA BASE

In the normal course of manufacturing, TriQuint measures FETs in process control monitors (PCM's) across each wafer, fits model elements to the measured S-parameter data, and stores this data along with a variety of other in-process data in its own database on a VAX mainframe computer. The data used for this study was gathered by measuring 112 FETs from 6 different runs, from a total of 14 wafers. The runs selected were those containing TriQuint MICRO-S (tm) standard products and were fabricated during the period of January 1987 to June 1987 with TriQuint's standard process.

The Fets measured have gate lengths of 0.5 um, width of 300 um (6 fingers of 50 um each), with gate-source spacing of 1.0 um and gate-drain spacing of 1.5 um. They were laid out with 50 um square probe pads in a Ground-Signal-Ground configuration. All FETs were biased at Vds = 4.0 V and Ids = Idss/2. Cascade Microtech's FET-FITTER II software [5] was used to control the measurement equipment and to fit the FET model lumped element values to the measured S-parameters. The model used for this study is shown in Figure 1.

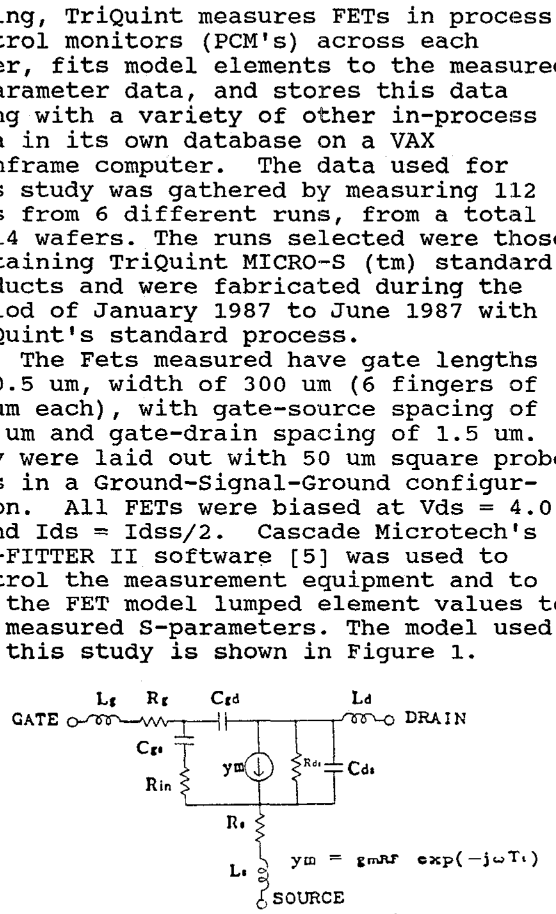

Figure 1- FET Lumped Element Circuit Model

1988 IEEE MTT-S Digest

From the 112 measured FETS the statistics for each FET model parameter were determined. The mean value, standard deviation, distribution function and correlation matrix were determined for each parameter. An example of the distribution and trend chart for Cgs and Cds are shown in Figures 2 and 3. Many of the parameter distributions were not "bell shaped". In fact several were bi-modal. The measured FET statistics are given in Tables 1 and 2.

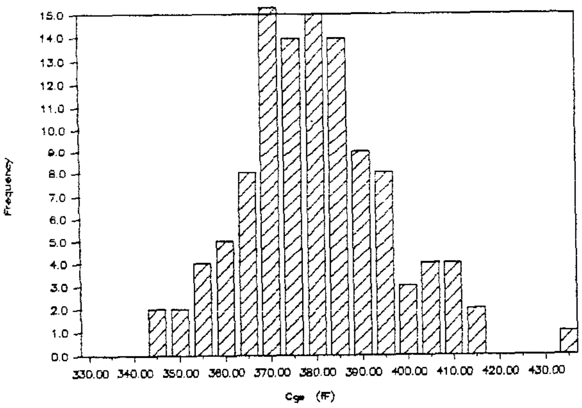

Figure 2- Distribution Chart for Cgs

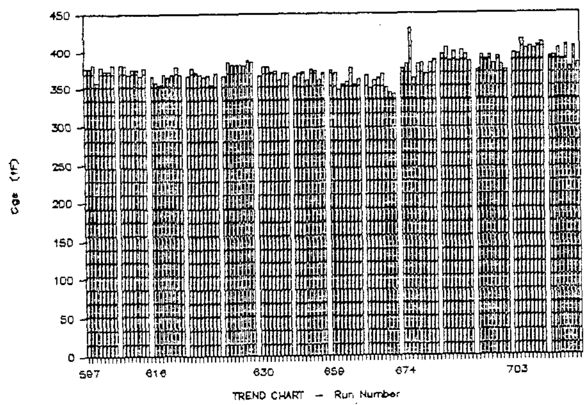

Figure 2- Trend Chart for Cgs

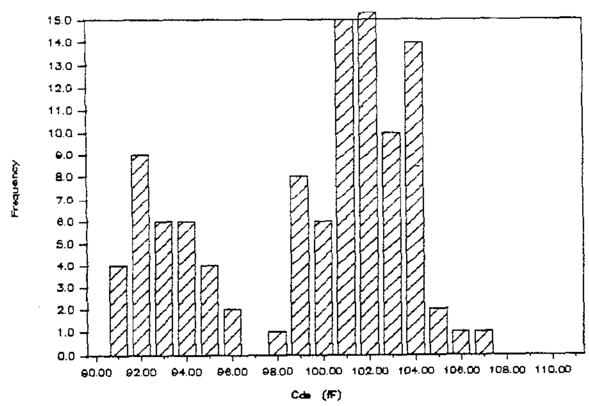

Figure 3- Distribution Chart for Cds

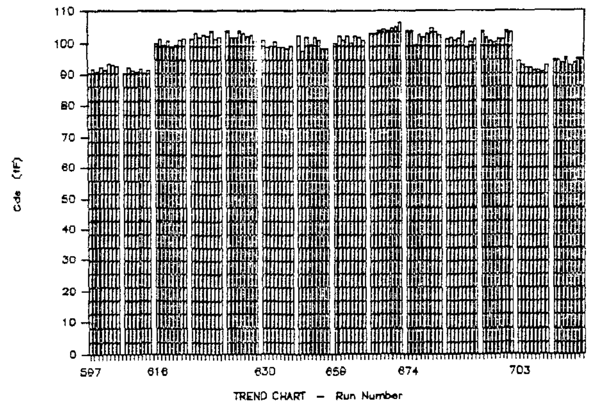

Figure 3- Trend Chart for Cds

	gm	Cgs	Cgd	Cds	Tt	Rin	Rs	Rds	Lg	Ls	Ld
gm	1.0	.78	.38	-.13	-.08	.03	-.26	.53	.15	.03	-.09
Cgs	.78	1.0	.15	-.24	.27	.21	-.35	.78	.25	.02	-.24
Cgd	.38	.15	1.0	-.04	-.46	-.04	.05	-.12	.04	-.14	.26
Cds	-.13	-.24	-.04	1.0	-.14	-.08	.23	-.26	-.20	-.44	.06
Tt	-.08	.27	-.46	-.14	1.0	.27	-.19	.41	.06	.04	-.16
Rin	.03	.21	-.04	-.08	.27	1.0	-.35	.53	-.01	-.14	-.04
Rs	-.26	-.35	.05	.23	-.19	-.35	1.0	-.52	.15	-.54	.12
Rds	.53	.78	-.12	-.26	.41	.53	-.52	1.0	.11	.11	-.28
Lg	.15	.25	.04	-.20	.06	-.01	.15	.11	1.0	-.22	-.16
L s	.03	.02	-.14	-.44	.04	-.14	-.54	.11	-.22	1.0	.02
Ld	-.09	-.24	.26	.06	-.16	-.04	.12	-.28	-.16	.02	1.0

Table 1- FET Model Parameter Correlation Matrix

Parameter	MEAN	STANDARD DEVIATION	%
gm	34.83	1.73	4.96
Cgs	377.40	15.69	4.16
Cgd	25.06	1.66	6.64
Cds	99.03	4.36	4.40
Tt	3.53	0.21	5.99
Rg	1.00	0.00	0.00
Rin	3.99	0.32	8.08
Rs	1.91	0.10	5.22
Rds	416.95	58.22	13.96
Lg	35.43	5.77	16.28
Ls	-0.30	1.26	-425.60
Ld	3.90	5.40	138.37

Table 2- FET Model Parameter Mean and Standard Deviation

DESIGN CENTERING SOFTWARE

This work uses Monte Carlo simulation to perform yield estimation and statistical circuit design in the same manner as described in [1]. This software system was updated to simulate the FET parameter statistics given in the TriQuint process data. Two options were available, one uses uniform uncorrelated FET parameters and the other uses the correlations and distributions given in the TriQuint data. The effects of these two options on statistical circuit design are explored using an example.

DESIGN CENTERING EXAMPLE

The circuit for this example is shown in Figure 4. The specifications for the amplifier are:

Frequency	3.8 - 4.2 GHz
S21 [dB]	> 14 db and < 16 dB
S11 and S22 [dB]	< -8 dB

The design centering procedure used in [1] was performed on this circuit under the

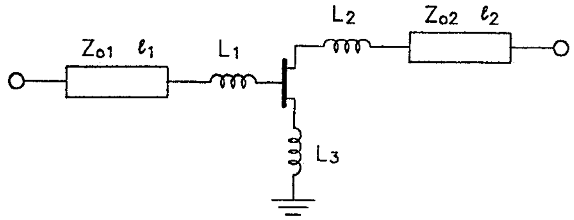

Figure 4- Design Centering Example Circuit

two assumptions on the FET parameter statistics: 1) uniform distributions (+/-1 sigma) and uncorrelated parameters and 2) distributions and correlations matching the TriQuint data. The other circuit parameters were varied +/- 10 percent using uniform uncorrelated distributions. The results of the centering process are shown in Table 3. The first conclusion to be drawn is that the FET parameter statistics have little effect on the parameter values for the statistically designed amplifier.

Yield prediction was then performed on the two designs:

- Design 1: statistically centered using uniform-uncorrelated FET parameters
- Design 2: statistically centered using distributed-correlated FET parameters

The yield prediction results are shown in Table 4. <u>The conclusion is that yield prediction can be strongly affected by the FET parameter statistics.</u>

3.7-4.2 GHz Amplifier

	UNIFORM/UNCORRELATED FET PARAMETERS		DISTRIBUTED/CORRELATED FET PARAMETERS	
Component	Initial Value	Centered Value	Initial Value	Centered Value
Z_1 (õ)	29.78	34.0	29.78	34.0
l_1 (cm)	1.875	1.875	1.875	1.875
L_1 (nH)	3.187	3.15	3.187	3.087
Z_2 (õ)	73.51	79.0	73.51	78.5
l_2 (cm)	1.875	1.95	1.875	1.95
L_2 (nH)	8.24	8.24	8.24	8.24
Yield	33.2%	50.0%	28.3%	46.3%

Table 3- Design Centering Results

Design 1: statistically centered with uniform-uncorrelated FET parameters
Design 2: statistically centered with distributed -correlated FET params.

DESIGN	Parameter Assumption	Yield Prediction
1	uniform-uncorrelated	50%
1	distributed-correlated	41.3%
2	uniform-uncorrelated	47.9%
2	distributed-correlated	46.3%

Table 4- Yield Prediction Results

FET S-PARAMETERS

An explaination of the above results should be possible when the FET S-parameters are studied under the above two statistical assumptions. The FET S-parameter distributions are presently unknown, but it is thought that the distributions are affected by the parameter statistics, and hence are responsible for the above results. The mean values and the correlations of the FET S-parameters do not significantly differ under the too assumptions. The calculated FET S-parameter correlation matrices at 4.0 GHz for the two FET parameter statistics are shown in Table 5. Notice that the correlations are not significantly different. This implies that the major contributor to the S-parameter correlations is the model structure rather than the parameter statistics. It is worthwhile noting here that it has not presently been determined if the measured and calculated S-parameter correlations are the same. This needs to be checked in order to statistically verify the FET model

UNIFORM AND UNCORRELATED

	S11	<S11	S21	<S21	S12	<S12	S22	<S22
S_{11}	1.0	.8	-.7	.9	-.3	.8	-.6	.2
$<S_{11}$		1.0	-.7	.9	-.3	.9	-.8	0.0
S_{21}			1.0	-.7	-.1	-.6	.6	.2
$<S_{21}$				1.0	-.3	.9	-.7	.2
S_{12}					1.0	-.5	.3	-.6
$<S_{12}$						1.0	-.7	.3
S_{22}							1.0	0.0
$<S_{22}$								1.0

DISTRIBUTED AND CORRELATED

	S11	<S11	S21	<S21	S12	<S12	S22	<S22
S_{11}	1.0	.9	-.3	.8	-.8	.8	-.6	0.0
$<S_{11}$		1.0	-.7	1.0	-.3	.9	-.7	0.0
S_{21}			1.0	-.7	0.0	-.6	.6	.2
$<S_{21}$				1.0	-.4	1.0	-.7	.2
S_{12}					1.0	-.5	.3	-.5
$<S_{12}$						1.0	-.7	.3
S_{22}							1.0	0.0
$<S_{22}$								1.0

Table 5- Calculated S-Parameter correlation matrix, 4.0 GHz

In the Appendix are trend and distribution charts for gm and Cgd. These are given to further document the measured FET statistics.

CONCLUSIONS AND FUTURE WORK

This study uses data collected from 112 FETs from 14 different wafers. Most of the FET parameter distributions are not "bell shaped". Some parameters are strongly correlated. Present-day CAD software does not allow these kinds of distributions and correlations for making yield estimates.

FET parameter statistics are important to statistical circuit design, especially to yield estimation values. For the example presented, design centering itself is insensitive to the FET statistics, and the uniform-uncorrelated assumption is satisfactory. However for accurate yield prediction, FET parameter statistics are important. Therefore if accurate yield estimation is to be performed by the design engineer, the correct FET statistics will have to be made available. A standard format for the statistical data needs to be developed. An equivalent study using FET S-parameters needs to be undertaken. It is not clear at this time whether FET model parameters or S-parameters will be more straigntforward to use statistically, but it is felt by the authors that FET model parameters will be better because of the strong frequency dependence of the S-parameter descriptions.

ACKNOWLEDGMENTS

We thank Warren Brakensiek for his work in developing the example. This work was supported, in part, by a subcontract funded through the DOD MIMIC Phase 0 Program, DAAL 01-86-BAA-0002.

APPENDIX

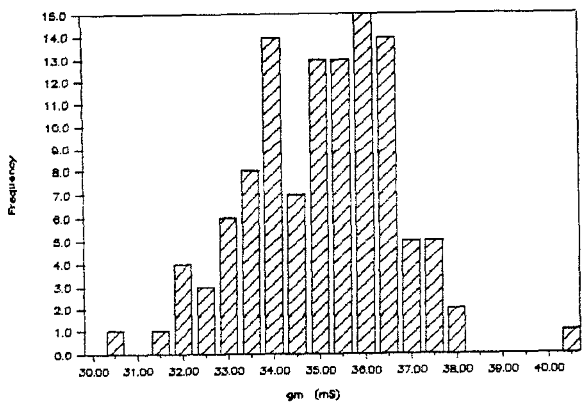

Figure 5- Distribution Chart for gm

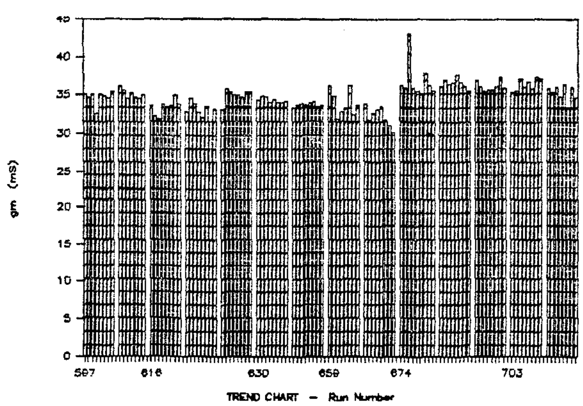

Figure 5- Trend Chart for gm

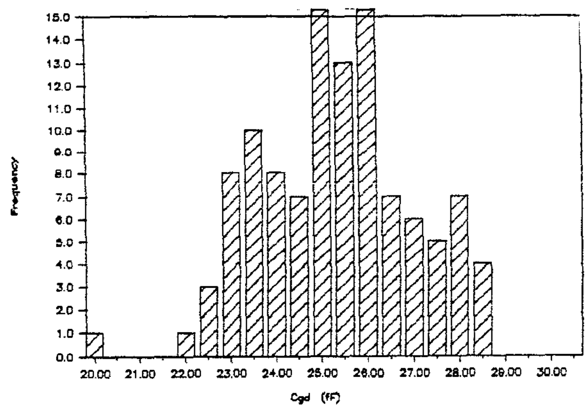

Figure 6- Distribution Chart for Cgd

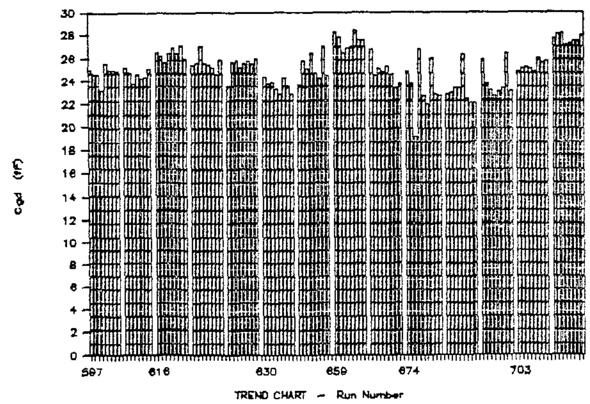

Figure 6- Trend Chart for Cgd

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