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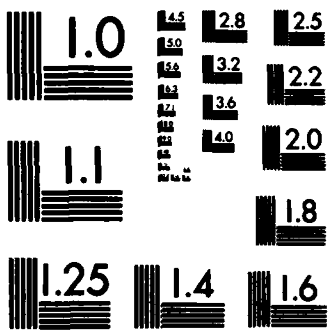

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A method has been developed for the statistical simulation of ~~GaAs MESFETs~~. Simulated device parameter distributions were compared with measured parameter distributions using the Kolmogorov-Smirnov test. By adjusting the individual input parameters in a trial and error process, an acceptable simulation was obtained for the parameter distributions of five different devices. The correlation coefficients between device parameters produced in the simulation were acceptable except for one parameter. A set of equations was derived for computing the parameters of the Curtice GaAs MESFET model in terms of six

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standard measured device parameters. A comparison of simulated and measured Curtice model parameters for the five devices did not indicate an acceptable match.

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THE UNIVERSITY OF TOLEDO

Report No. UT EE 83-21

STATISTICAL SIMULATION OF GAAS MESFETS

Final Scientific Report for

USAF Grant No. AFOSR-82-0119

Arthur R. Thorbjornsen
Professor of Electrical Engineering
The University of Toledo
Toledo, Ohio 43606

August 29, 1983

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1.0 RESEARCH OBJECTIVES

The goals of the research effort, as stated in the research grant proposal were (1) to develop a method for the statistical simulation of gallium-arsenide metal-semiconductor field-effect transistors (GaAs MESFETs), (2) to include in the method functional relationships between the basic physical variables in device fabrication and the electrical model parameters of Curtice's model for the GaAs MESFET, and (3) to compare the data generated by the GaAs MESFET statistical simulation program with measured device data.

A statistical simulation of an electronic device involves the generation of many sets of values for the parameters in a mathematical model of the device. The generated sets of device model parameter values can then be used in a circuit analysis program to produce a Monte Carlo analysis, which is useful in circuit design.

The generated sets of device parameter values must have distributions and correlations which are reasonable approximations to those of measured sets of device parameter values. Ideally, the generated and measured data should be indistinguishable from one another. Since the mathematical models of electronic devices involve many approximations it is probably impossible to achieve an ideal simulation.

2.0 STATUS OF THE RESEARCH

The accomplishments and progress towards achieving the research objectives are as follows:

(1) A method has been developed, and implemented as a computer program for the statistical simulation of GaAs MESFETs. The method involves the generation of sets of random numbers (having normal distributions and in most cases being independent) to represent the geometrical and material (physical device) parameters in device fabrication. A set of nonlinear equations relating the physical device parameters to the voltage and current behavior of the device is solved numerically to produce computed values for several device electrical parameters. The nonlinear equations cause the electrical parameters to have realistic distributions and correlations.

(2) A set of equations was derived that relates a standard set of device electrical parameters, which can be measured directly, into a set of parameters for Curtice's model of the GaAs MESFET. The parameters used in Curtice's model cannot be measured directly.

(3) The data generated by the statistical simulation program has been compared with measured device data. Measured electrical parameter data for five different GaAs MESFETs was obtained. Each device was simulated using the program and the simulated electrical parameter values were compared to measured values by two methods -- (a) by visual inspection of parameter frequency histograms and scatter diagrams and (b) by use of the two-sample Kolmogorov-Smirnov test for goodness-of-fit. By using optimum input parameters for individual devices, the results of the simulation program passed the Kolmogorov-Smirnov test for about 45% of the electrical parameters. Since the K-S test is very rigorous, a more practical criterion was determined for judging the simulation results. With the more practical criterion, about 75% of the simulated device parameters have acceptable distributions. Judging by the scatter diagrams, all but one of the six parameters for a device have the proper correlation with respect to the other parameters. The one exception is probably due to the approximations that are part of the simplified mathematical model of a complex physical device. This method for statistical simulation of GaAs MESFETs may prove to be adequate for purposes of circuit design, but further testing with more measured device data will be necessary to properly assess the adequacy of the method.

3.0 TECHNICAL JOURNAL PUBLICATIONS PLANNED

The following manuscript is currently being prepared and will be submitted to either the IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems or the IEEE Journal of Solid-State Circuits:

Title: "A Method for the Statistical Simulation of GaAs MESFETs"

Author: A. R. Thorbjornsen

4.0 PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

The only person who worked on this research project was the principal investigator, Dr. Arthur R. Thorbjornsen of The University of Toledo.

5.0 DETAILED DESCRIPTION OF THE RESEARCH

5.1 Background

In the design of integrated circuits it is desirable to be able to accurately simulate the performance characteristics of a circuit prior to setting up an IC facility for fabrication. It is difficult, and in some cases impossible to make changes to an integrated circuit after fabrication. Also, the cost of preparing for IC fabrication is very high so it is essential that the finished circuit operate as desired and that the circuit yield be as high as possible.

A technique for obtaining very complete information on circuit performance and also an indication of circuit yield is the Monte Carlo circuit analysis method. A Monte Carlo analysis will produce a sample of values of all of the circuit performance characteristics from which one can compute such statistics as the means, standard deviations, skewness, and correlation coefficients and also plot frequency histograms, giving an indication of the distribution shapes of the performance characteristics.

For a Monte Carlo circuit analysis to give accurate results it is necessary to have accurate statistical models of the various devices that make up an integrated circuit. The statistical model should account for the distribution shapes of the device parameters as well as the correlations between parameters.

In the area of silicon bipolar integrated circuits an early method made use of factor analysis to relate the variations of most parameters to an independent parameter [1]. Maly and Strojwas have developed a method of statistically simulating circuit performance in terms of the parameters of the IC manufacturing process [2]. Diaz has developed a method for the statistical simulation of bipolar junction transistors in terms of material and device dimensional variables which produces accurate device parameter distribution shapes and correlations [3].

In the area of GaAs MESFET ICs there has apparently been no work on statistical simulation. Since GaAs fabrication technology is relatively immature there are very large device parameter variabilities ($\pm$ 60% variabilities are common in devices constructed at the USAF Avionics Laboratory) which makes the need for statistical design techniques greater than if there were small variabilities.

5.2 Methodology

The distributions of device parameters often have non-normal shapes, which, coupled with the inherent correlation between integrated device parameters, makes the generation of sets of parameter values very difficult. The standard random number generating subroutines usually produce uniform or normal distributions. The generation of sets of correlated random numbers having normal distributions is a trivial matter [4].

What must be done is to start the simulation process by generating correlated, normally distributed random numbers and then to process those numbers to produce the correlated, non-normally distributed random numbers that accurately simulate measured device parameter values. The device variables that can be assumed to have normal distributions are the device dimensions and the material variables such as dopant concentration, electron mobility, etc. These dimensional and material variables will be referred to as the input physical parameters.

Various models have been developed for solid-state devices which relate the input physical parameters described above to electrical device behavior. Most of these mathematical device models consist of sets of nonlinear equations which must be solved numerically.

Therefore, the methodology to be used in this research is to numerically solve a set of nonlinear model equations for the electrical parameters characterizing a GaAs MESFET. The input to the nonlinear equations will be sets of normally distributed values of the dimensional and material variables of the device plus physical constant values. The output will be sets of values of electrical device parameters which will have distributions and correlations that are as realistic as the mathematical model will permit.

5.3 Mathematical Device Model Used

A two-region GaAs MESFET model developed by Pucel, Haus, and Statz was chosen to be used in this research [5,6]. The two-region model accounts for the fact that in GaAs, at high levels of electric field strength, the electron velocity is limited to a saturation value. In one region of the model the electron mobility is assumed to be constant and in the other region the electron velocity is assumed to be constant. The dividing line between the two regions depends on the applied terminal voltages.

Figure 1 shows the two-region model of the intrinsic device coupled to the parasitic drain and source resistances which forms the extrinsic device model used in this study.

The equations describing the intrinsic device behavior are:

$$V_{13} = V_p \{(u_c^2 - u_1^2) + \frac{2t}{\pi z L} \sinh [\frac{\pi(L-L_1)}{2t}]\} , \qquad (1)$$

$$L_1 = zL \, [(u_c^2 - u_1^2) - \frac{2}{3}(u_c^3 - u_1^3)]/(1 - u_c) , \qquad (2)$$

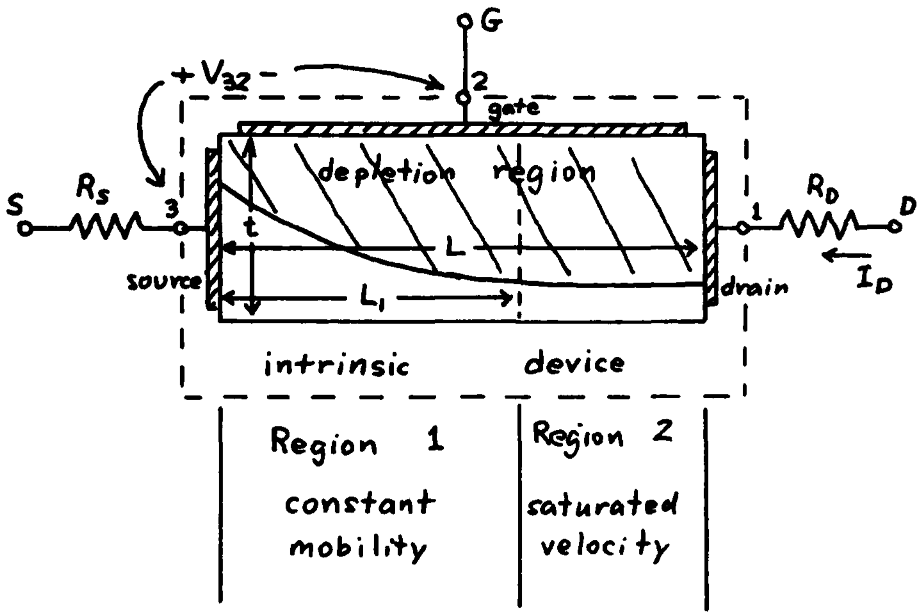


Figure 1. The extrinsic GaAs MESFET model.

$$I_D = q\, N_d\, v_s\, t\, W(1 - u_c) \;, \tag{3}$$

and

$$u_1 = [(V_{32} + V_{bi})/V_p]^{1/2} \;, \tag{4}$$

where

$$V_p = q\, N_d\, t^2/2\varepsilon_s$$

and

$$z = \mu_n\, V_p/v_s L \;.$$

Also, v_s is the saturated velocity in region 2, L is the total channel length, L_1 is the channel length of region 1, W is the gate width, u_c is the normalized depletion layer thickness at the boundary between regions 1 and 2, u_1 is the normalized depletion layer thickness at the source end of the channel, t is the thickness of the active GaAs layer, N_d is the concentration of donor electrons in the GaAs active layer, ε_s is the permitivity of GaAs, μ_n is the electron mobility in GaAs, V_{bi} is the built-in potential of the gate junction, and q is the magnitude of the charge of an electron.

The parasitic source resistance is given by

$$R_s = \frac{L_{AS}}{qN_d\mu_n tW} + \frac{4\text{x}10^{-5}}{L_{CS}W\sqrt{N_d}} \;.$$

The first term in the expression for R_S is the resistance of the bulk material between the channel and the source contact. The second term is the contact resistance [7]. L_{AS} is the distance between the gate and source contacts plus 0.8 micrometer and L_{CS} is the length of the source contact. A similar equation is used for R_D. The terminal device equations are

$$V_{DS} = I_D(R_S + R_D) + V_{13} \tag{5}$$

and

$$V_{GS} = I_D R_S - V_{32} . \tag{6}$$

Equations (1) through (6) contain the eight unknown variables V_{DS}, V_{GS}, V_{13}, V_{32}, I_D, L_1, u_c, and u_1. Since there are only six equations, two variables must be assigned values. For example, V_{DS} and V_{GS} are usually assigned values and then the equations are solved to find the value of I_D. The six unknown variables must be supplied with initial estimated values. The method of solution used is the standard Newton-Raphson method [8].

5.4 Form of Measured Device Data

The standard GaAs MESFET electrical parameters that are routinely measured at the USAF Avionics Laboratory are the following:

I_{DSS} = the saturation drain current with V_{GS} = 0.0 volts and V_{DS} = 2.5 volts,

V_T = the pinchoff voltage, or the value of $-V_{GS}$ at which I_D = 0.01 x I_{DSS} and V_{DS} = 2.5 volts,

R_{LIN} = the drain to source resistance in the linear region with V_{GS} = 0.0 volts,

R_{OM} = the drain to source resistance in saturation with V_{GS} = 0.0 volts,

R_D = the parasitic drain resistance,

R_S = the parasitic source resistance,

G_m = the transconductance,

V_{knee} = the drain to source voltage at the knee of the I-V curve with V_{GS} = 0.0 volts,

and V_{G-chan} = the gate to channel forward voltage drop.

The first six parameters, I_{DSS} through R_S, are sufficient to compute the parameters for the Curtice model (see the next section) so they were chosen as the parameters to be simulated. The definitions of the first four parameters are illustrated in Figure 2.

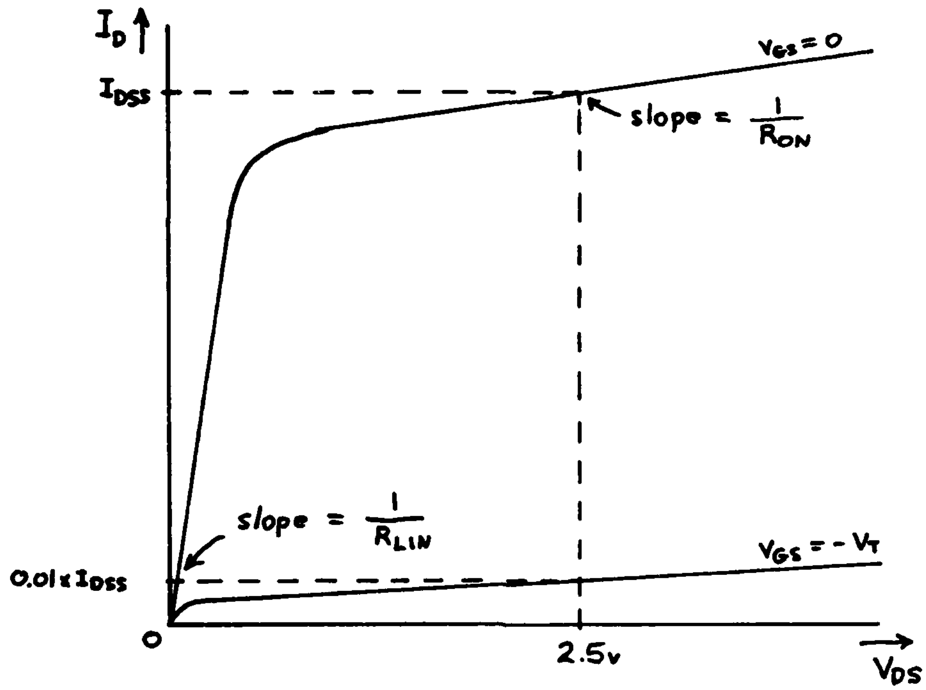


Figure 2. Measured MESFET parameters.

The Device Technology Group at the Avionics Laboratory at Wright-Patterson Air Force Base supplied measured data for five transistors all fabricated on the same chip. There were about 50 samples of each transistor on wafer number 86S82. The identification numbers of the devices are F16, F22, F24, F27, and F31.

A small computer program was written to compute the mean values, standard deviations, and correlation coefficients for each of the parameters of all five devices. Frequency histograms and scatter diagrams were also plotted. The frequency histograms show the distribution shape and the scatter diagrams show if the correlations between parameters are linear or nonlinear.

5.5 Derivation of Equations for the Curtice Model Parameters

One of the more accurate models for the GaAs MESFET is that proposed by Curtice [9]. We will consider only the dc version of Curtice's model, shown in Figure 3, for which the drain current is given by

$$I_D = \beta(V_{23} + V_T)^2 \; (1 + \lambda V_{13}) \; \tanh(\alpha V_{13}) \; . \tag{7}$$

α, β, and λ are the electrical model parameters and cannot be directly measured. We desire to be able to solve for α, β, and λ in terms of the

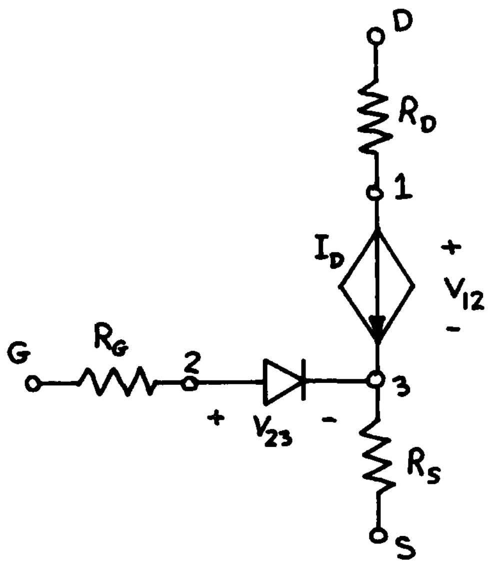


Figure 3. The dc version of Curtice's model of the GaAs MESFET.

measured parameters I_{DSS}, V_T, R_{ON}, R_{LIN}, R_S, and R_D. R_S and R_D are already part of the Curtice model and we shall ignore the parasitic gate resistance R_G. The definitions of I_{DSS}, R_{LIN}, and R_{ON} will be used in conjunction with equation (7) to derive equations for α, β, and λ.

The saturation drain current is the value of I_D when $V_{GS} = 0.0$ volts and $V_{DS} = \hat{V}_{DS} = 2.5$ volts. Since V_{DS} is large, V_{13} will also be large and tank$(\alpha V_{13}) \simeq 1.0$. Equation (7) will thus be reduced to

$$I_{DSS} = \beta(V_{23} + V_T)^2 \ (1 + \lambda V_{13}) \tag{8}$$

and equations (5) and (6) become

$$V_{13} = \hat{V}_{DS} - I_{DSS} \ (R_S + R_D) \tag{9}$$

and

$$V_{23} = -I_{DSS} \ R_S \ . \tag{10}$$

Equations (8), (9) and (10) are combined to give

$$\beta = \frac{I_{DSS}}{V_T - I_{DSS} R_S)^2 \{1 + \lambda [\hat{V}_{DS} - I_{DSS} (R_S + R_D)] \}} \ . \tag{11}$$

The definition of R_{ON} is

$$R_{ON} = \left.\frac{\partial V_{DS}}{\partial I_D}\right|_{\substack{V_{GS} = 0 \\ V_{DS} = \hat{V}_{DS} = 2.5v}} \tag{12}$$

Using equation (5) we have

$$\frac{\partial V_{DS}}{\partial I_D} = \frac{\partial V_{13}}{\partial I_D} + (R_S + R_D) \tag{13}$$

and from equation (8)

$$\frac{\partial I_D}{\partial V_{13}} = \lambda\beta(V_{23} + V_T)^2 \; . \tag{14}$$

Substituting equations (13) and (14) into (12) and solving for λ produces

$$\lambda = \frac{1}{\beta(V_T-I_{DSS}R_S)^2[R_{ON}-(R_S+R_D)]} \; . \tag{15}$$

Substituting equation (15) into (11) and solving gives us the final expression for β.

$$\beta = \frac{I_{DSS}}{(V_T-I_{DSS}R_S)^2} - \frac{[\hat{V}_{DS}-I_{DSS}(R_S+R_D)]}{(V_T-I_{DSS}R_S)^2[R_{ON}-(R_S+R_D)]} \tag{16}$$

R_{LIN} is defined as

$$R_{LIN} = \left.\frac{\partial V_{DS}}{\partial I_D}\right|_{\substack{V_{DS} = 0 \\ V_{GS} = 0}} \; , \tag{17}$$

where the partial derivative can be expressed by equation (13). Taking the derivative of equation (7) with respect to V_{13} results in

$$\frac{\partial I_D}{\partial V_{13}} = \beta(V_{23}+V_T)^2\{\lambda\tanh(\alpha V_{13})+\alpha(1+\lambda V_{13})\,\mathrm{sech}^2(\alpha V_{13})\}. \tag{18}$$

The conditions defined in equation (17) means that $V_{13} = 0$ and $V_{23} = 0$, therefore equation (18) reduces to

$$\frac{\partial I_D}{\partial V_{13}} = \alpha\beta V_T^2 \tag{19}$$

and R_{LIN} is given by

$$R_{LIN} = \frac{1}{\alpha\beta V_T^2} + (R_S+R_D) \quad . \tag{20}$$

Equation (2) is solved for α resulting in

$$\alpha = \frac{1}{\beta V_T^2 [R_{LIN} - (R_S+R_D)]} \quad . \tag{21}$$

The parameters in Curtice's model can now be computed in terms of the standard measured electrical parameters defined in section 5.4 using equations (15), (16), and (21). The value for β must first be calculated since it is used in the calculation of α and λ.

5.6 The Statistical Simulation Method

The method for the statistical simulation of GaAs MESFETs consists of the following steps:

1. Generate N normally distributed random numbers for each of the input physical parameters N_d, t, L,W, V_{bi}, L_{AS}, L_{AD}, L_{CS}, and L_{CD} having specified means, standard deviations, and correlation coefficients.
2. Compute R_S and R_D using the equation given in section 5.3 for one set of input physical parameter values.
3. For the same set of input parameter values, solve equations (1) through (6) for I_{DSS} with V_{GS} = 0.0 volts and $V_{DS} = \hat{V}_{DS}$ = 2.5 volts using the Newton-Raphson method.
4. Using the same set of input parameter values as above, solve equations (1) through (6) for V_{DS1} with I_{D1} = 0.004 mA and V_{GS} = 0.0 volts. Compute $R_{LIN} = V_{DS1}/I_{D1}$.
5. Using the same set of input parameter values, solve equations (1) through (6) for I_{D2} with V_{DS2} = 2.0 volts and V_{GS} = 0.0 volts. Compute $R_{ON} = (\hat{V}_{DS}-V_{DS2})/(I_{DSS}-I_{D2})$.
6. Using the same set of input parameter values as above, solve equations (1) through (6) for V_{GS3} with $I_D = 0.01 \times I_{DSS}$ and V_{DS} = 2.5 volts. The pinchoff voltage is $V_T = -V_{GS3}$.
7. Repeat steps 2 through 6 for each set of input physical parameter values.
8. Compute a set of α, β, and λ values for each set of values of V_T, I_{DSS}, R_{LIN}, R_{ON}, R_D, and R_S using equations (15), (16), and (21).

9. Calculate the statistics for each of the computed device parameters and plot frequency histograms and scatter diagrams.

A computer program was written that performs the above steps and was used for the simulations described in the following sections.

Very infrequently a set of input physical parameter values will result in nonconvergence of the Newton-Raphson technique. When this condition occurs the Newton-Raphson method terminates after 40 iterations, that particular set of input parameter values is discarded, and the next set tried. Typically, the Newton-Raphson method will converge in from 90% to 100% of all cases. For one device the convergence rate was closer to 50%.

5.7 Statistical Test for Goodness-of-Fit

In some other papers the results of statistical simulations are compared to measured data by tabulating side-by-side the means, standard deviations, and correlation coefficients computed from simulated and measured data [1,2]. Usually no quantitative measure is given of how well the simulated results match the measured results. What should be done is to perform a statistical test giving a quantitative measure of whether or not a set of simulated parameter values and a set of measured parameter values have the same distribution, or come from the same population. One such test is the two-sample Kolmogorov-Smirnov goodness-of-fit test [10,11]. The Kolmogorov-Smirnov (K-S) test uses as a measure of goodness-of-fit the maximum absolute difference between two discrete cumulative distribution functions.

The K-S test statistic, $D_{m,n}$, must be less than a certain value (which is dependent on the two sample sizes, m and n) in order to be able to accept the hypothesis that the two distributions are the same at a certain level of significance. The level of significance used in this research was 0.95, which means that there is a 0.05 probability of accepting a false hypothesis.

Figure 4 shows the superimposed, normalized frequency histograms for measured and simulated values of the parameter I_{DSS} for device F22. Device F22 had the best overall match between simulated and measured results. The test statistic for I_{DSS} was $D_{m,n} = 0.128$ with a critical value of 0.225 at a level of significance of 0.95. This test statistic value of 0.128 indicates that the two distributions are the same. Upon inspection of Figure 4 one sees that the two means are nearly identical, the lower limits are the same, the upper limits differ quite a bit, and the amplitudes differ substantially from point to point.

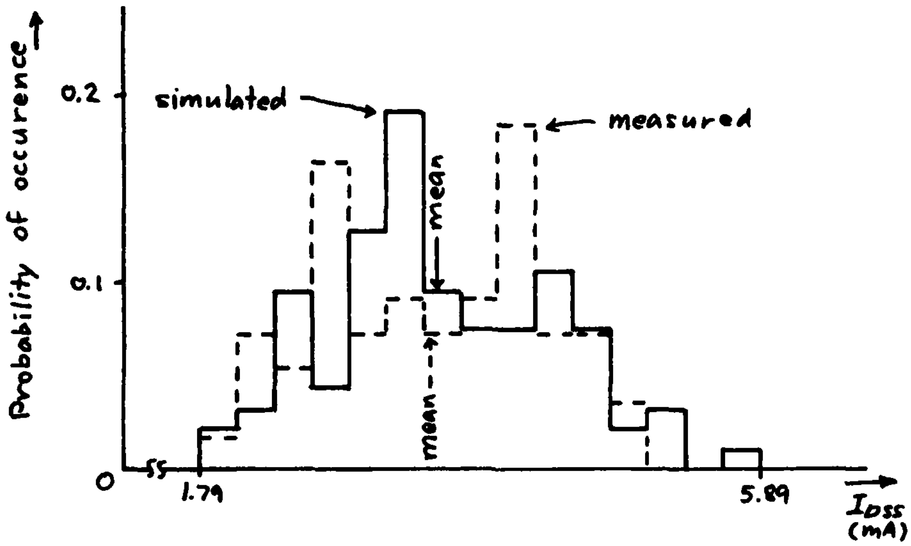


Figure 4. Frequency histograms for I_{DSS}, device F22.

The author feels that the Kolmogorov-Smirnov test is extremely rigorous and that for practical, or design, purposes a less rigorous criterion should be used. After inspecting the results of many simulations it was decided that a test statistic value of 0.33 would produce an acceptable match. Figure 5 shows the superimposed, normalized frequency histograms for measured and simulated values of a parameter for which the computed test statistic is equal to 0.33. In Figure 5 the means are not identical but the distributions have fairly similar shapes and cover almost the same range of values.

5.8 Simulation of Individual Devices

In order to statistically simulate the five devices for which measured data had been provided, it was necessary to use trial and error to find the best set of values for the means, standard deviations, and correlation coefficients of the input physical parameters for each of the five devices. These individual best fit mean values are listed in Table 1.

Table 2 lists the mean values of the fixed input parameters for each device. The actual distance from the gate contact to the drain or source contact is $0.8\text{x}10^{-4}$ cm less than the L_A value shown in Table 2. In the

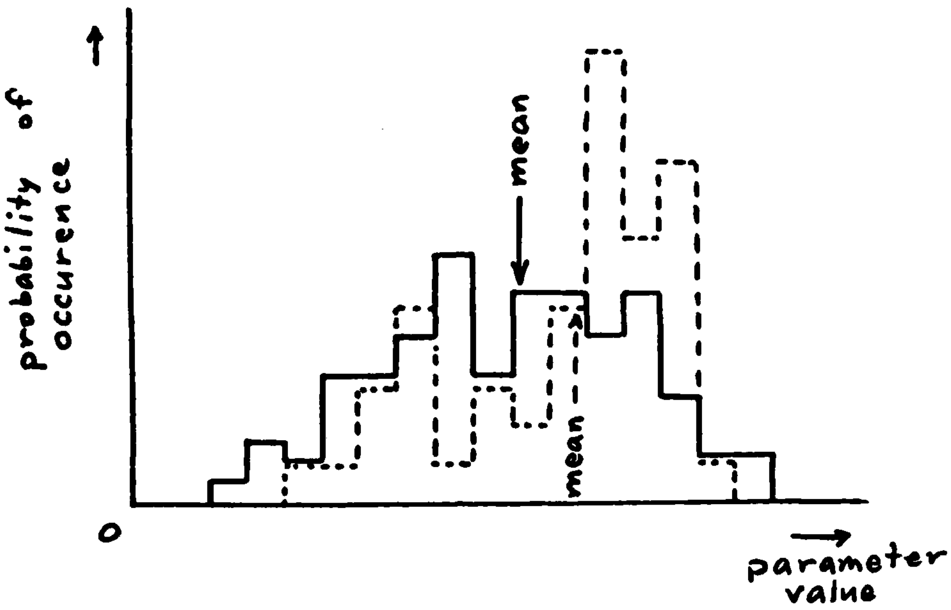


Figure 5. Frequency histograms for which the test statistic is equal to 0.33.

Table 1. Individual best fit input parameter mean values.

Device	$N_d(cm^{-3})$	v_s (cm/sec)	t (cm)	V_{bi} (volts)
F16	0.78×10^{17}	1.3×10^7	0.25×10^{-4}	0.8
F22	0.73×10^{17}	1.6×10^7	"	"
F24	0.65×10^{17}	1.7×10^7	"	"
F27	0.78×10^{17}	1.3×10^7	"	"
F31	0.78×10^{17}	1.3×10^7	"	"
Ave.	0.744×10^{17}	1.44×10^7	"	"

case of F27 the actual G-D spacing is 2.6×10^{-4} cm and the actual G-S spacing is 2.4×10^{-4} cm but 2.5×10^{-4} cm was used for both dimensions.

The input parameter standard deviation values listed in Table 3 were used for all five devices. The standard deviations of all surface dimensions were

Table 2. Mean Values of fixed input parameters.

Device	W (cm)	L (cm)	L_C (cm)	L_A (cm)
F16	23×10^{-4}	0.8×10^{-4}	4.0×10^{-4}	3.8×10^{-4}
F22	23×10^{-4}	1.6×10^{-4}	"	2.8×10^{-4}
F24	23×10^{-4}	2.0×10^{-4}	"	2.8×10^{-4}
F27	13×10^{-4}	0.8×10^{-4}	"	3.3×10^{-4}
F31	13×10^{-4}	1.0×10^{-4}	"	2.8×10^{-4}

assumed to be the same.

All of the input physical parameters except the pairs L_{AS}, L_{AD} and L_{CS}, L_{CD} were assumed to be independent or noncorrelated. The correlation coefficients used for the pair L_{AS}, L_{AD} was -0.98 and for the pair L_{CS}, L_{CD} was 0.6. The gate contact is made separately from the drain and source contacts so any shift in the gate contact position would cause L_{AS} to increase and L_{AD} to decrease, or vice versa. Since the drain and source contacts are made using the same photomask operations, those two lengths should be positively correlated.

Table 3. Input parameter standard deviations.

Parameter	Standard Deviation
W	0.133×10^{-4} cm
L	0.133×10^{-4} cm
L_A	0.133×10^{-4} cm
L_C	0.133×10^{-4} cm
V_{bi}	0.05 volts
t	0.25×10^{-5} cm
N_d	0.1×10^{16} cm^{-3}

Using the individual best fit parameter values listed above the five devices were simulated and then the results were compared with the measured data using the Kolmogorov-Smirnov test. The results of the K-S tests are listed in Table 4. 46.7% of the test statistic values in Table 4 are less than the critical value, which means that nearly half of the simulated parameters have the same distributions as their measured counterparts.

Table 4. Results of the K-S test using individual best fit input parameter values.

Parameter	K-S test statistic value				
	F16	F22	F24	F27	F31
I_{DSS}	0.272**	0.128*	0.225*	0.199*	0.169*
R_{ON}	0.530	0.211*	0.110*	0.220*	0.272**
R_{LIN}	0.287**	0.198*	0.437	0.514	0.546
R_D	0.296**	0.237**	0.232*	0.204*	0.589
R_S	0.309**	0.229**	0.211*	0.361	0.384
V_T	0.275**	0.128*	0.175*	0.249**	0.196*
Critical Value	0.233	0.225	0.241	0.232	0.225

* less than the critical value

** less than the acceptable value of 0.33

76.7% of the test statistic values are less than 0.33, meaning that there is an acceptable match between simulated and measured distributions in over 3/4 of the cases.

Device F22 has the best overall match as all test statistic values are less than 0.33 and four of the six are less than the critical value. Figure 4 illustrates the match between measured and simulated frequency histograms for parameter I_{DSS} of device F22.

In Table 5 are listed the computed correlation coefficients for the simulated and measured parameters for device F16. The upper number in each square was computed from measured data and the lower from simulated data. Although no statistical test was performed, one can see that the correlation coefficients match quite well. There is one exception in the case of parameter R_{ON} for which the measured and simulated correlation coefficients have the opposite signs. It is believed that this discrepancy is due to the two-region GaAs MESFET model not being perfectly descriptive of device behavior. There are many assumptions and simplifications in the derivation of equations (1) through (6).

Two examples of scatter diagrams are given in Figures 6 and 7 to show both the good and the bad matches that were obtained. Figure 6 shows the measured and simulated scatter diagrams of I_{DSS} vs. R_{LIN} for device F16.

Table 5. Computed correlation coefficients for device F16.

	I_{DSS}	R_{LIN}	R_{ON}	R_D	R_S
R_{LIN}	-0.956 -0.967				(measured) (simulated)
R_{ON}	0.629 -0.969				
R_D	-0.455 -0.818	0.535 0.809	-0.142 0.797		
R_S	-0.921 -0.895	0.913 0.877	-0.549 0.893	0.256 0.556	
V_T	0.993 0.993			-0.498 -0.845	-0.892 -0.869

The measured scatter diagram shows a small degree of curvature which is also present in the simulated scatter diagram. The correlation coefficients are almost identical.

Figure 7 illustrates the discrepancy noted above in the correlations involving parameter R_{ON}. The measured scatter diagram has a positive slope while the simulated one has a negative slope.

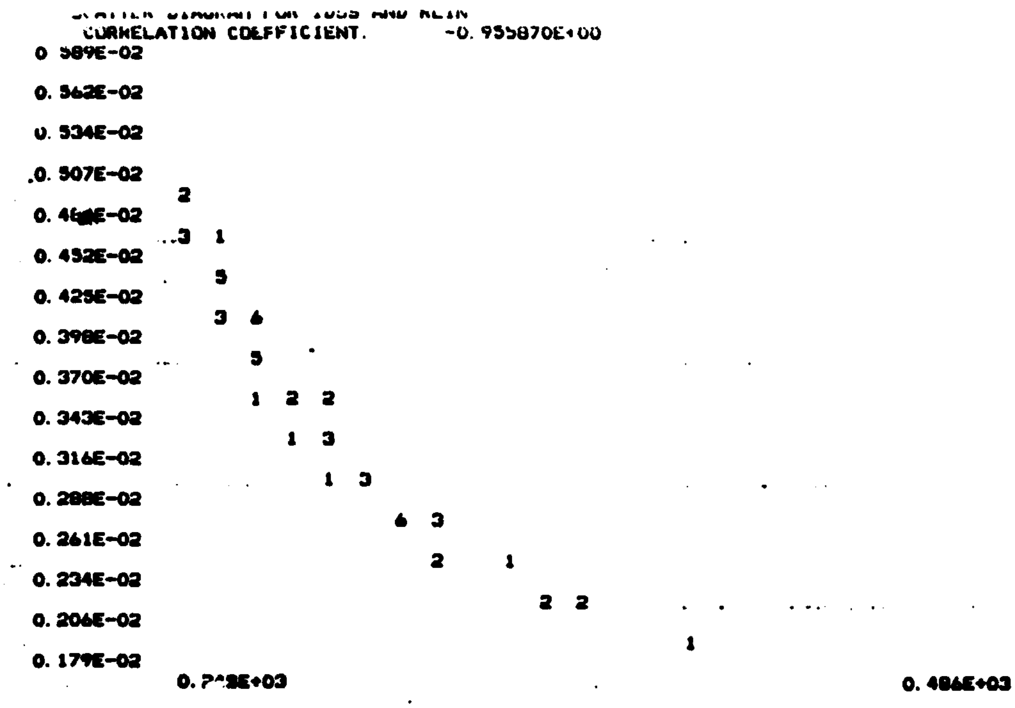
The values of the Curtice model parameters were also computed using the statistical simulation program and compared to the values obtained from measured data using the Kolmogorov-Smirnov test. The results of the tests are given in Table 6.

Table 6. Results of the K-S test on the Curtice model parameters.

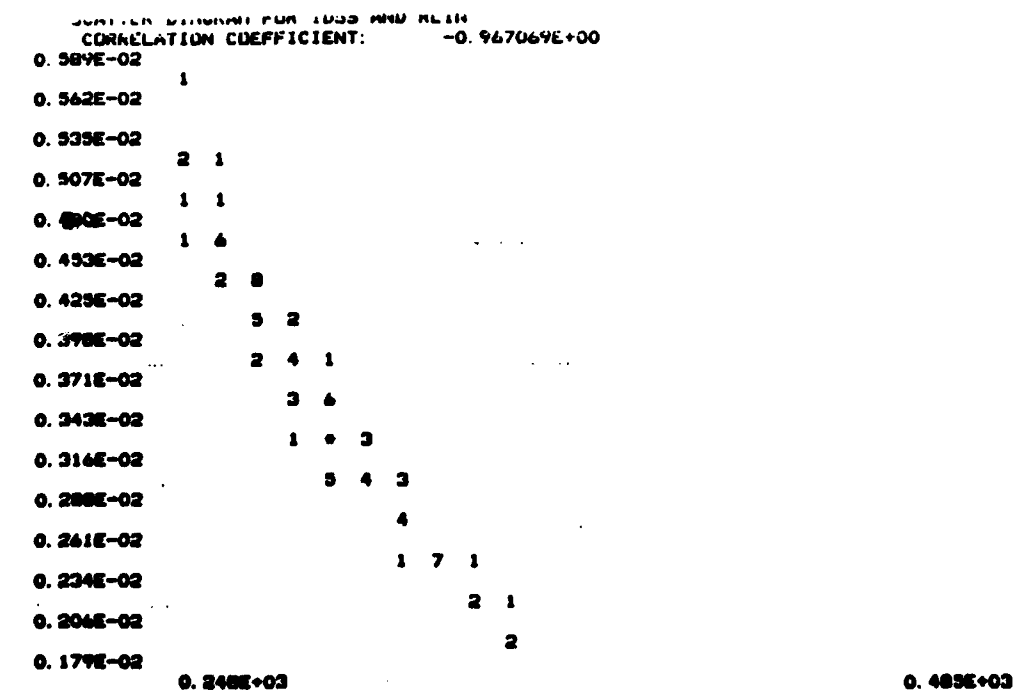
	K-S test statistic value				
Parameter	F16	F22	F24	F27	F31
α	0.989	0.503	0.915	1.000	0.818
β	0.413	0.323**	0.140*	0.329**	0.232**
λ	0.680	0.473	0.466	0.423	0.509
Critical Value	0.233	0.255	0.241	0.232	0.225

* less than critical value
** less than acceptable value of 0.33

β is the only parameter which is simulated to an acceptable degree in nearly all devices.

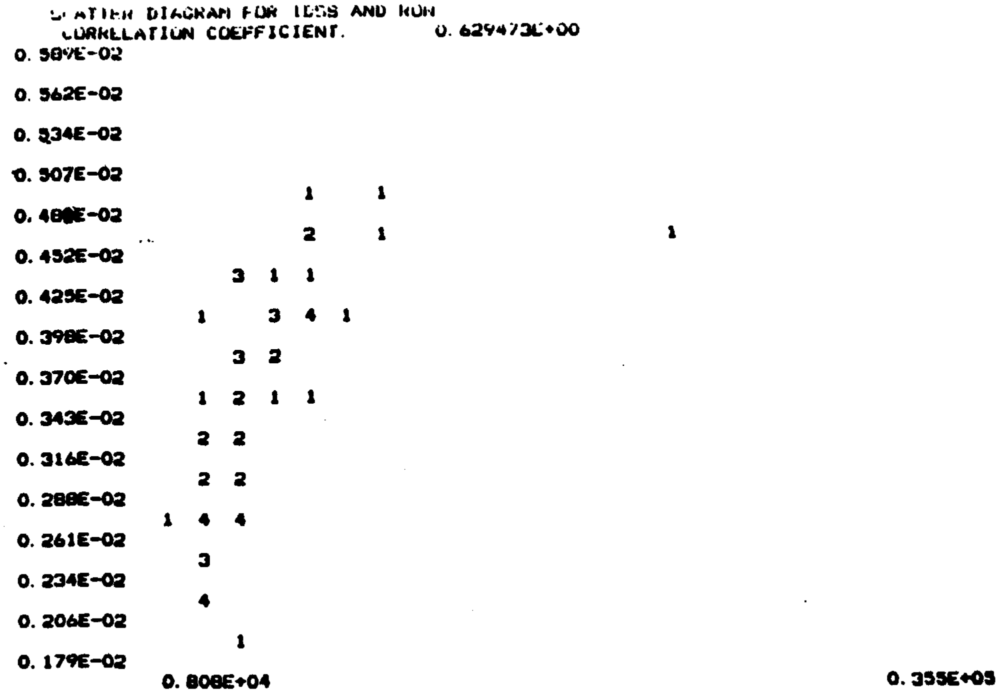


(a)

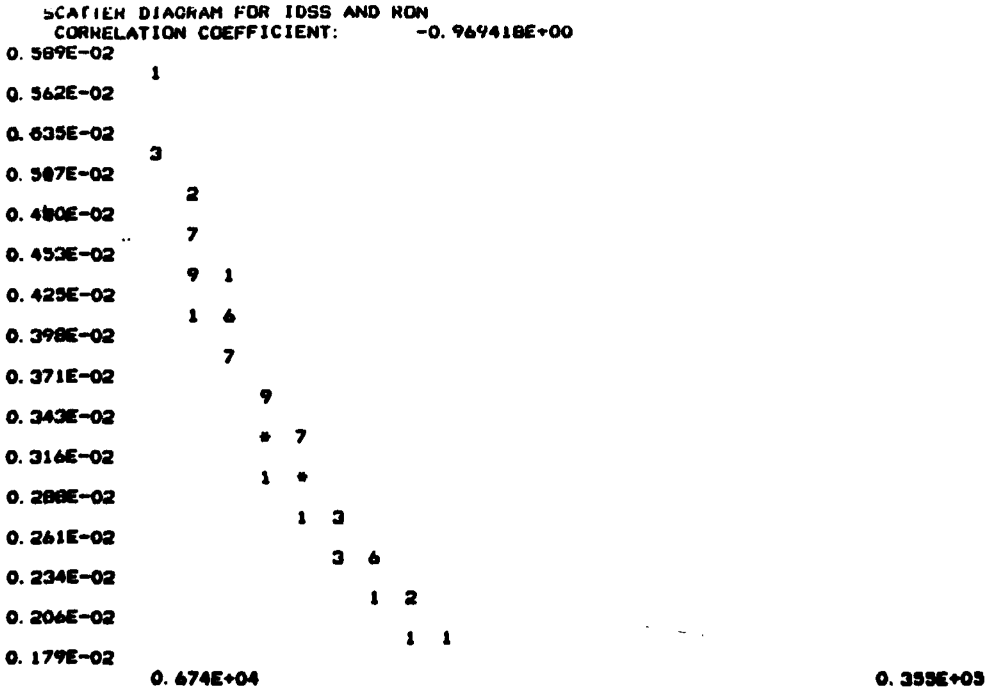


(b)

Figure 6. Scatter diagrams of I_{DSS} vs R_{LIN} for device F16.
(a) From measured data. (b) From simulated data.



(a)



(b)

Figure 17. Scatter diagrams of I_{DSS} vs R_{ON} for device F16.
(a) From measured data. (b) From simulated data.

Table 7 lists the correlation coefficients between α, β, and λ. Here there is a very poor match between simulated and measured results. It is believed that the problem with the correlations involving R_{ON} is primarily responsible for these poor results because the equations for β and λ both contain the term R_{ON} in the denominator.

Table 7. Computed correlation coefficients for device F16.

	α	β
β	-0.913 0.386	(measured) (simulated)
λ	-0.833 0.001	0.820 0.944

5.9 Simulation of a Group of Devices

Ideally, a statistical simulation method should be able to simulate several different devices using the same mean values for some of the input physical parameters that would be expected to be common for all devices on the same chip. The mean values of N_d, v_s, t, and V_{bi} should be the same for all devices on the same chip but N_d and v_s had to be varied in order to obtain the individual best fit results of the previous section.

A simulation was performed using the average of the best fit input parameter values as the input for all five devices. The results of the K-S tests of these simulations is given in Table 8. Of the computed test statistic values only 30% are less than the critical value and only 36.7% are less than the acceptable value of 0.33. Again, device F22 has the best match between simulated and measured distributions.

6.0 CONCLUSIONS

A method for the statistical simulation of GaAs MESFETs has been developed and tested. For practical, or design, purposes the method seems to do an acceptable job of simulating the standard measured device parameters although the correlations involving parameter R_{ON} have the wrong sign. This problem may be due to the device model equations not being entirely accurate. There may also be a problem with the measured values of R_{ON} that were supplied since a small number of values seemed to occur over and over again. Normally one would expect a random spread of parameter values, as was the case with

Table 8. Results of the K-S test using average best fit input parameter values.

Parameter	K-S test statistic value				
	F16	F22	F24	F27	F31
I_{DSS}	0.328**	0.131*	0.345	0.201*	0.179*
R_{ON}	0.619	0.480	0.454	0.374	0.447
R_{LIN}	0.354	0.155*	0.407	0.431	0.420
R_D	0.735	0.354	0.842	0.308**	0.486
R_S	0.636	0.183*	0.618	0.481	0.433
V_T	0.221*	0.171*	0.491	0.184*	0.150*
Critical Value	0.233	0.225	0.232	0.234	0.225

* less than critical value

** less than acceptable value of 0.33

the other parameters.

The simulation method did not do an adequate job of simulating the Curtice model parameters. In this case the Curtice model parameters had to be computed both from measured and from simulated data so computational error (because of approximate equations) could have been at fault.

The method of computing the parameters of Curtice's model from the standard measured parameters does not involve any iterative numerical techniques as do the parameter extraction methods, hence the results will not be as accurate as those from parameter extraction programs.

7.0 RECOMMENDATIONS FOR FURTHER RESEARCH

Follow-on research should include the testing of other GaAs MESFET mathematical models in the statistical simulation method in an effort to find a model that produces accurate simulations. In order to obtain accurate simulations of the Curtice model parameters it may be necessary to use the statistical simulation program to produce many points on the device I-V characteristics and then to use a parameter extraction program to extract the Curtice model parameters, as is done with measured device data.

The simulation method used in this research simulates individual GaAs MESFET devices to an acceptable accuracy. When performing Monte Carlo analyses of integrated circuits it is necessary to simulate groups of devices with correlation between the parameters of different devices. The statistical simulation method should be extended to simulate groups of devices and then should be coupled to a circuit analysis program, such as SPICE2, to produce accurate Monte Carlo circuit analyses.

Further research can make use of the above mentioned Monte Carlo circuit analysis program to study GaAs MESFET circuit designs and to develop Monte Carlo analysis as a circuit design tool.

8.0 REFERENCES

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