# A Complete GaAs MESFET Computer Model for SPICE

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***Abstract*** **—A model for the gallium arsenide MESFET has been implemented into the source code of the well-known circuit simulation program SPICE. Both large-signal and small-signal simulations of MESFET circuits are now possible within the familiar framework and data format of SPICE. The line-by-line modifications made to SPICE to achieve the model implementation will be made available to interested researchers.**

## I. Introduction

The potential of GaAs MESFET's in digital integrated circuits (DIC's) and monolithic microwave integrated circuits (MMIC's) is now generally recognized to be quite significant. In the U.S., the government recently has announced [1] a Defense Advanced Research Projects Agency program to set up GaAs foundries for DIC's. This action reflects the success that has been realized in the development of ultra-high-speed logic circuits [2]. GaAs devices also have been used extensively in a wide variety of MMIC realizations, such as amplifiers, phase shifters, frequency converters, oscillators, and switches [3], [4]. Yet, unlike the case for silicon integrated circuits, where general purpose circuit simulators such as SPICE [5], complete with sophisticated device models, have been available for many years in the public domain, programs to perform large- and small-signal modeling of GaAs IC's, when available at all (e.g., [6], [7]), have generally been company proprietary. When SPICE has been used in the past to simulate GaAs MESFET circuits, the standard JFET model was often employed in place of a true GaAs FET model. However, this approach has been shown [7] to yield considerable error in the various computed circuit responses. In this report, we describe our implementation of the GaAs model of [7] into SPICE. Our model implementation duplicates the performance of the R-CAP [6] version of the model described in [7], and includes a small-signal, as well as a large-signal, modeling capability. Details of the modifications to the source code of SPICE 2G.5 will be made available to interested researchers upon request.

## II. The GaAs MESFET Model and Its Installation in SPICE

The model for the $n$-channel GaAs MESFET developed by Curtice [7] is shown in Fig. 1 and is described by the following equations:

$$I(V_{GS}, V_{DS}) = \beta (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \tanh(\alpha V_{DS})$$

$$C_{GS} = C_{GSO}/(1 - V_{GS}/V_{BI})^{1/2}$$

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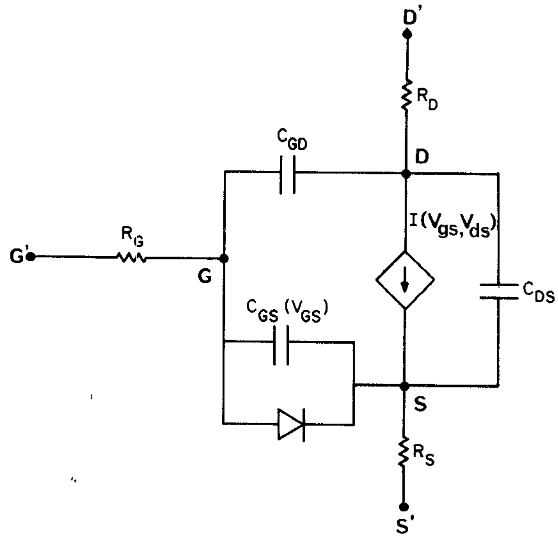


Fig 1. Curtice's GaAs MESFET model.

where

| | |
|---|---|
| $V_T$ | threshold voltage, |
| $\beta$ | transconductance parameter, |
| $\lambda$ | channel length modulation parameter, |
| $\alpha$ | hyperbolic tangent function parameter, |
| $R_D, R_S, R_G$ | resistances of contact regions, |
| $C_{GD}, C_{DS}$ | constant interelectrode capacitances, |
| $C_{GS}$ | nonlinear gate-source capacitance, |
| $C_{GSO}$ | $C_{GS}$ for $V_{GS} = 0$, |
| $V_{BI}$ | (positive) built-in voltage at the gate. |

The transit time under the gate, $\tau$, is also a model parameter, although the dependency upon $\tau$ is not stated explicitly in the above equations. The diode in the model is ideal and is specified by the single parameter $I_S$, the reverse saturation current, which is chosen to correspond to the gate leakage current. The diode is also needed to provide device clamping as $V_{GS}$ increases towards zero from its normally negative values.

We note parenthetically that our extension of this model to include small-signal behavior is based upon the standard technique of constructing an incremental equivalent circuit at a specific dc operating point. Inasmuch as Curtice's original application was the modeling of large-signal transient phenomena in GaAs digital circuits, it cannot be stated unequivocally that the corresponding small-signal model will automatically provide accurate device scattering parameters for use, say, in microwave amplifier design. However, a satisfactory resolution of this matter is not expected to be terribly difficult and, in fact, will be addressed by us in a future paper.

To install the GaAs MESFET model into SPICE requires detailed knowledge of the internal structure of the program. Some of this information is available in [8], but anyone attempting to modify SPICE, which contains some twenty-thousand relatively unstructured FORTRAN statements, will soon find the available documentation inadequate for anything other than a starting point for a considerable amount of additional work. However, for those researchers who have experience in the modification of SPICE, we have prepared a brief description of SPICE's data structures and the particular linked-list [9] specifi-

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cations for the GaAs FET *device* and the GaAs FET *model*, which SPICE distinguishes between within its source code. This information, which is available from the first-named author, will be useful to those who might want to perform further modifications to SPICE for additional models, perhaps. The specific changes made to SPICE to achieve the implementation of the GaAs MESFET model required the extensive modification of fifteen subroutines and the addition of one totally new subroutine. It is impracticable to present here the several hundred lines of code describing this procedure; rather, we shall make available, again upon request to the first-named author, a documented floppy disk with the complete source-code listings of all the updated and added subroutines. The installation of the new model into SPICE can then be achieved by simply following the line-by-line changes given in the listings. The names of the FORTRAN subroutines within SPICE2G.5 that have to be modified to include the new model are as follows: READIN, FIND, ADDELT, MODCHK, ERRCHK, TOPCHK, LNKREF, MATPTR, MATLOC, DCTRAN, LOAD, TRUNC, ACLOAD, DCOP, and ELPRNT. The added subroutine, which contains the GaAs FET equations, is called, simply, GASFET.

## III. User's Guide for the GaAs MESFET Model

The MESFET model in SPICE is described by the following parameters and default values.

| *Name* | *Parameter* | *Default Value* |
|---|---|---|
| VTO | Threshold voltage | −2.5 V |
| VBI | Built-in gate potential | 1.0 V |
| RG | Gate resistance | 0 |
| RD | Drain resistance | 0 |
| RS | Source resistance | 0 |
| ALPHA | Hyperbolic tangent parameter | 2.0/V |
| BETA | Transconductance parameter | 1.0E−4 A/V**2 |
| LAMBDA | Channel length modulation parameter | 0 |
| CGSO | Zero-bias gate-source capacitance | 0 |
| CGS | Gate-drain capacitance | 0 |
| CDS | Drain-source capacitance | 0 |
| IS | Gate leakage current | 1.0E−14A |
| TAU | Transit time undergate | 0 |

The general form of the device card for the GaAs MESFET is

$$Bxxx \text{ ND NG NS MNAME IC} = V_{DS}, V_{GS}$$

for example

$$B1\ 1\ 2\ 3 \text{ GFET}.$$

ND, NG, and NS are the external drain, gate, and source nodes, respectively, of the device, and correspond to nodes $D'$, $G'$, and $S'$ in Fig. 1. MNAME is the user-specified model name. The optional initial condition specification begins with IC and is intended for use with the UIC option on the .TRAN card as described in the SPICE user's guide. The general form of the model card is

.MODEL MNAME GASFET(parameter1 = value1, · · · )

for example

.MODEL GFET GASFET(VTO = −2.0, VBI = 1.1, RD = 3.).

Model parameters not assigned values on the model card will assume their respective default values. In our implementation, just as for all other device models in SPICE, the program automatically constructs the small-signal model for the GaAs FET when such an analysis is requested in the data file.

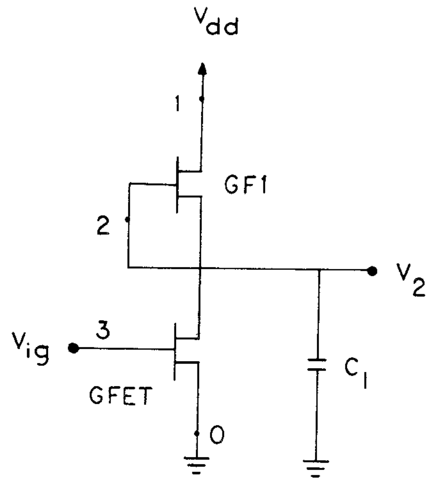


Fig. 2. MESFET logic gate.

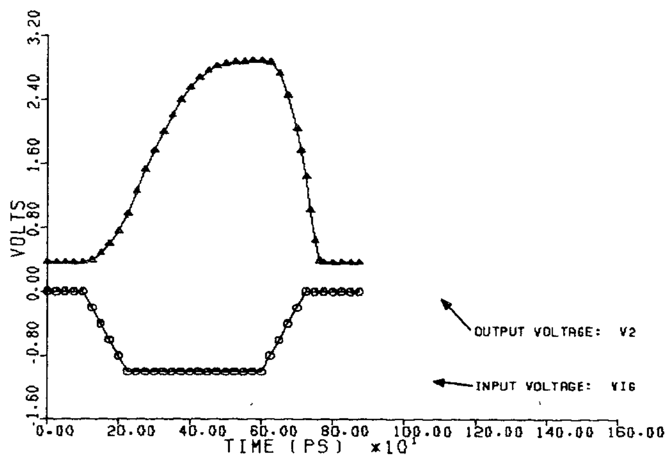


Fig 3 Response of MESFET logic gate from SPICE2G.5.

We were able to duplicate all the results that Curtice [7] achieved with his model in R-CAP [6] with this same model now installed by us in SPICE. We illustrate one of these coincident results in the Appendix, where the SPICE data file is displayed for the MESFET logic gate of Fig. 2, which is the same as that used by Curtice in his example from [7, figs. 10–12]. The response of the logic gate, as computed by SPICE, to a trapezoidal voltage excitation is shown in Fig. 3. Our results with SPICE are identical to Curtice's calculations performed using R-CAP.

## IV. Conclusion

The implementation of a GaAs MESFET model into SPICE has been described, and the availability of the corresponding modifications to SPICE has been announced. It is hoped that the new model, now available in the public domain, will prove to be most useful to GaAs MESFET researchers. Future work is anticipated to develop the capability of determining model parameters to optimally fit a set of small-signal scattering parameters across a frequency band.

## Appendix

### SPICE Data File for MESFET Inverter

```
* TRANSIENT RESPONSE OF GAAS MESFET INVERTER
*
VDD 1 0 3.5
VIG 3 0 PULSE (0 −1 100PS 125PS 125PS 375PS 1S)
B1 1 2 2 GF1
```

```
B2 2 3 0 GFET
CL 2 0 6F
.MODEL GFET GASFET(VTO = -2.5, BETA = 65U, VBI = .5,
ALPHA = 1.5, TAU = 10PS)
.MODEL GF1 GASFET(VTO = -2.5, BETA = 32.5U, VBI = .5,
ALPHA = 1.5)
.TRAN .0125NS INS
.PRINT TRAN V(3) V(2)
.PLOT TRAN V(3) V(2) (-1 4)
.END
```

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# Letters

## Comment on "Microwave Diffraction Tomography for Biomedical Applications"

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In the above paper [1], and a subsequent publication [2], Bolomey *et al.* suggested a very useful technique of biological tomography which may provide a fast image reconstruction at low cost. In a more recent work [3], Bolomey also presented some interesting results of a reconstructed image of a pony kidney. The virtue of the suggested technique lies in the rapidity of data collection by modulated scattering. Here we would like to point out that more theoretical study is still needed on the interpretation of the reconstructed image. The algorithm of the technique is based on the identity

$$\tilde{E}(\alpha,\beta;z)=\tilde{E}(\alpha,\beta;z_0)\,e^{i(z-z_0)\sqrt{k_m^2-\alpha^2-\beta^2}} \qquad (1)$$

where $\tilde{E}(\alpha,\beta;z)$ is the Fourier transformation (FT) of the electric field in the $xy$-plane and $k_m$ is the wavenumber in the medium surrounding the target. Thus, from measurements of $\vec{E}$ in a plane at $z=z_0$, one may predict the field in another parallel plane by simply making an FT followed by an inverse FT. However, it must be pointed out that the above identity is valid only when both planes are outside the target (the pony kidney in this case) and on the same side of the target.

To illustrate this point, let us consider a scalar field of a point source located at $\vec{x}=0$. The field is given by $A(\vec{x})=\exp(ik_m r)/r$. A measurement of the field in the plane $z=z_0$ $(z_0>0)$ will yield

$$A(x,y,z_0)=\frac{\exp\left(ik_m\sqrt{x^2+y^2+z_0^2}\right)}{\sqrt{x^2+y^2+z_0^2}}$$

of which the FT is

$$\tilde{A}(\alpha,\beta;z_0)=i\frac{\exp\left(i|z_0|\sqrt{k_m^2-\alpha^2-\beta^2}\right)}{\sqrt{k_m^2-\alpha^2-\beta^2}}$$

where, for $\alpha^2+\beta^2>k_m^2$, the square root is taken to have a positive imaginary part so that $\tilde{A}$ decays exponentially for large $\alpha^2+\beta^2$. Applying (1) and taking the inverse FT, one gets

$$A_R(x,y,z)=\frac{i}{2\pi}\int_{-\infty}^{\infty}d\alpha\int_{-\infty}^{\infty}d\beta \cdot e^{i(\alpha x+\beta y)}\frac{\exp\left[i\sqrt{k_m^2-\alpha^2-\beta^2}\,(|z_0|+z-z_0)\right]}{\sqrt{k_m^2-\alpha^2-\beta^2}} \qquad (2)$$

where the subscript $R$ denotes that it is a reconstructed field. Clearly, (2) gives the correct field as long as $z$ and $z_0$ are both positive. But, if $z<0$ while $z_0>0$, the integral in (2) diverges because of the exponential factor. Of course, one may always truncate the integrand at $\alpha^2+\beta^2=k_m^2$, as it is always done in practical computation. Then the integration gives approximately $A_R(x,y,z)=-\exp(-ik_m r)/r$. Thus, the field reconstruction using (1) produces an outgoing wave in one side of the source and an incoming wave in the opposite side of the source, whereas the actual field is an outgoing wave in both sides of the source. For a continuous distribution of sources, $J(\vec{x})$, in a region $V$, the actual

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