V. Conclusion

A numerical method used to solve for the frequency-dependent characteristics of symmetric, asymmetric, and offset inductive and capacitive gaps in shielded slotline and microstrip lines has been presented. With a simple yet accurate basis function, this technique leads to an accurate evaluation of the equivalent circuit parameters of these discontinuities.

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An Improved GaAs MESFET Model for SPICE

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***Abstract*—A SPICE model has been developed to more accurately model GaAs MESFET devices. In particular, small-signal parameters such as the *S* parameters are accurately modeled over a wide range of bias conditions. These results were achieved by modifying the Statz [1] model equations to better represent the variation of I_{ds} as a function of the applied voltage.**

The model applies over a large range of pinch-off voltages, allows size scaling of devices, and is suited for modeling R_{ds} changes with frequency. The Statz equations are used to represent diode characteristics and capacitive components of the model.

I. Introduction

Since the commercial development of GaAs MESFET IC technology, the past decade has seen a proliferation of proposed models for GaAs MESFET's. Of these, the most frequently cited and most widely used are the models proposed by Curtice [2] and an improved model put forward by Statz *et al.* [1]. The Curtice model is derived from the Shichmann–Hodges JFET model [3] modified to provide a proper knee voltage for the $I-V$ curves. The Statz model additionally provides an improved representation of the capacitance behavior.

The purpose of the current work is to model specific features of MESFET behavior which neither the Curtice nor the Statz equations properly describe. It is shown that the resulting model equations provide an improved fit to measured MESFET characteristics without increased complexity.

II. Deficiencies of Existing Models

A typical result obtained when attempting to fit the Statz model to measured $I-V$ data is illustrated in Fig. 1. Notice particularly the slope of the $I-V$ curves, the drain conductance.

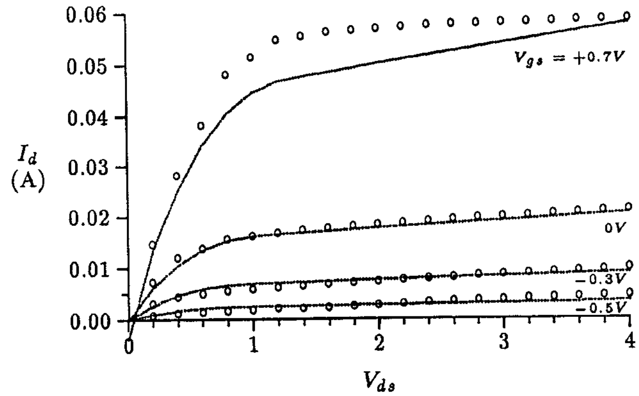

Fig. 1. As illustrated for a 0.6 V pinch-off GaAs MESFET, the Statz model (solid lines) shows poor tracking of the drain–source resistance as the gate bias is varied. The model parameters were chosen to fit measured data (∘) at an intermediate gate bias.

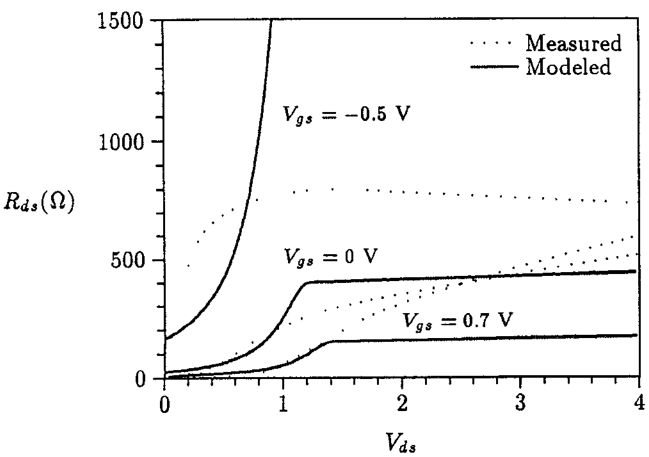

Fig. 2. The Statz model does not track measured drain resistance, R_{ds}, well as the gate bias is varied. The measured data are extracted from S-parameter data. As illustrated in the figure, the tracking is especially poor when V_{gs} is near cutoff. The sharp change in slope near 1.2 V is a result of using the cubic polynomial approximation in the Statz equations.

As with most proposed GaAs MESFET models, the drain conductance is modeled by multiplying the expression for I_{ds} by a term: $(1+\lambda V_{ds})$. While this term can represent drain conductance at a particular bias point, it does not model variations with bias correctly, predicting a conductance which increases at higher values of I_{ds}, while the observed conductance actually decreases.

The Statz model also fails to provide an accurate model at low currents where V_{gs} is near cutoff. In particular, the drain conductance derived from the Statz equation, illustrated in Fig. 2, does not fit well.

The differences between the measured and modeled dc $I-V$ curves are reflected in erroneous predictions of small-signal parameters such as gain and drain resistance over the dynamic range of the device. The improper tracking of these parameters with bias leads to incorrect predictions of such performance characteristics as gain compression and harmonic distortion.

Proposed models that fit drain conductance variations better than the Statz model include that by Materka [4] and the Curtice cubic [5], but these models suffer from other disadvan-

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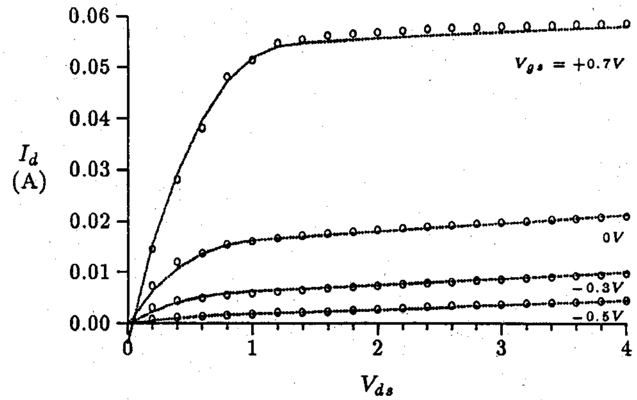

Fig. 3. A better fit to measured data is evident when the improved model is used. In contrast to the Statz model, the conductance slope is modeled over a wide range of bias conditions. For this device, $V_{t0} = -0.7$ V; $\beta = 1.15\times10^{-4}$ A/V^2, $\delta = 0.56$/W, $\gamma = 0.044$, $\alpha = 2.7$ V^{-1}.

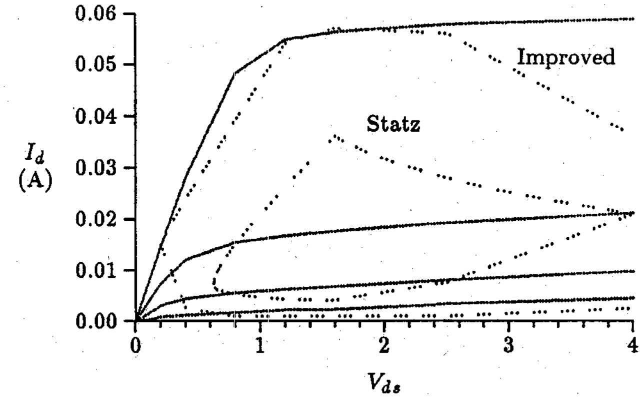

Fig. 5. A comparison between the Statz and improved models can be seen in the above figure. The inscribed contours represent a maximum error of 0.2 for S_{11}, S_{22}, or S_{12}, or a maximum error of 20% in S_{21} parameters for each of the models. The larger area occupied by the improved model is indicative of the improved fit.

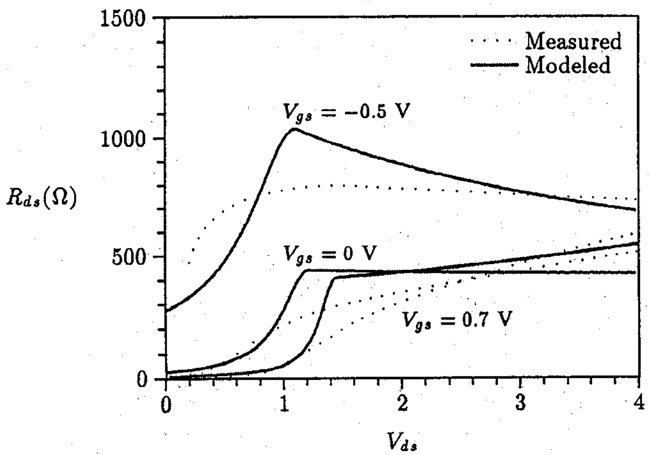

Fig. 4. The improved model tracks drain resistance, R_{ds}, better as the gate bias is varied. The sharp change in slope near 1.2 V is a result of using the cubic polynomial approximation.

tages. The Materka model is useful only for depletion devices due to the form of the drain current equations. The Curtice cubic uses empirically determined series expansion parameters which are difficult to relate to physical descriptions of the devices. Our model is usable for depletion and enhancement devices and can be accurately scaled with device size.

III. The Improved Model

A modification of the Statz model corrects the deficiencies outlined above. The Statz expression for the dc drain current is given by

$$I_{ds} = \frac{\beta(V_{gs} - V_t)^2(1+\lambda V_{ds})}{1+b(V_{gs}-V_t)} \mathrm{Ktanh}(\alpha V_{ds}). \tag{1}$$

In this equation, β, α, V_t, λ, and b are (constant) model parameters and $\mathrm{Ktanh}(x)$ denotes a polynomial approximation to the tanh function devised by Statz to decrease computation times.

The first modification to these equations is designed to address the poor fit at near pinch-off values of V_{gs}. This is accomplished by making V_t a function of drain voltage:

$$V_t = V_{t0} - \gamma V_{ds}. \tag{2}$$

This improves the drain conductance fit at low drain currents, where the Statz model shows a cutoff independent of drain voltage. The utility of (2) has also been noted by other workers [5], [4].

The second modification relates to the way in which I_{ds} decreases at higher values of current and voltage, showing a smaller slope than would be predicted from the cited models, possibly even becoming negative. We use an equation which models this as a feedback effect:

$$I_{ds} = \frac{I_{ds0}}{1+\delta V_{ds} I_{ds0}} \tag{3}$$

where δ is a (new) model parameter, and I_{ds0} is given by the expression

$$I_{ds0} = \beta(V_{gs} - V_t)^Q \mathrm{Ktanh}(\alpha V_{ds}). \tag{4}$$

This equation resembles the Statz equation (1) with b and λ set equal to zero. The parameter Q is necessary to model the non-square-law dependence of I_{ds} which is observed for devices with small or positive pinch-off voltage, and has been found useful by other workers [6].

Notice the new parameters γ and δ *replace* λ and b in the Statz model. Capacitances and gate diode characteristics are adapted from the Statz formulas [1]. Figs. 3 and 4 illustrate the improved agreement between the model equations and measured data.

IV. High-Frequency Characteristics: S Parameters

The good fit to the dc $I-V$ characteristics is not the only reason for using the improved model. It also provides a better model for ac characteristics, such as S parameters, over a wider bias range. Fig. 5 shows the increased bias range over which the improved model provides accurate RF characterization. The

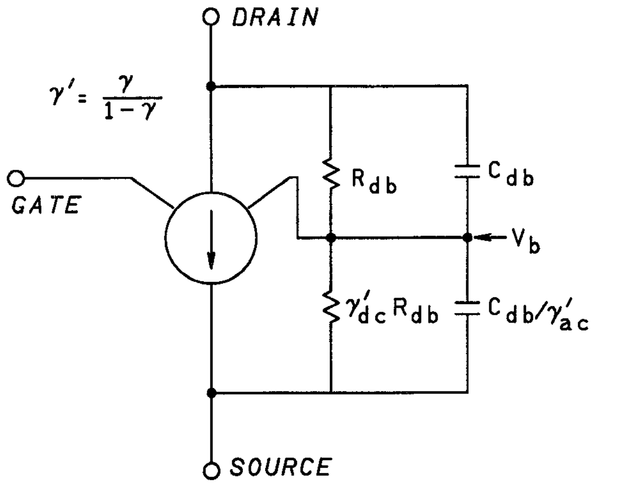

Fig. 6. This equivalent circuit model of a GaAs MESFET helps clarify the physical meaning of the parameter γ. The current source in the model is controlled by the sum of the gate voltage and an assumed "back-gate" voltage, V_b. For additional explanation, see the text.

plot presents contours of constant S-parameter vector error superimposed on the drain $I-V$ curves. The contours show a 20% vector error between measured S parameters and S parameters generated with either the Statz or the improved model. The inner curve depicts the Statz model and the outer represents our modified model. Note that the improved model contour encloses the area for large voltage and low currents as well as low drain voltage and large currents. This results in improved accuracy for gain compression and other nonlinear parameters. As an example of the nonlinear capabilities the 1 dB output compression was simulated in PSPICE for a 900 MHz low-noise amplifier. The measured value on a breadboard amplifier was +1.5 dBm. The Statz model predicted +2.2 dBm and the improved model predicted +1.9 dBm.

V. Low-Frequency Effects: R_{ds} Versus Frequency

GaAs MESFET's exhibit substantial changes in the value of drain resistance R_{ds} at low frequency [6], [7]. The large value at dc decreases with frequency, leveling off somewhere around 1 MHz. The parameter most directly influencing R_{ds} in the model is γ. For the devices studied, the only necessary change to convert a model matching the dc characteristics to one matching the high-frequency characteristics is γ. The ability to change between ac and dc models lends itself to being able to use one model to match the entire frequency range.

Such a model is represented in Fig. 6. This equivalent circuit model of a GaAs MESFET helps clarify the physical meaning of γ. The current source in the model is controlled by the sum of the gate voltage and an assumed "back-gate" voltage, V_b. Other models in the literature represent the current source as being directly driven by the gate–source voltage. The back-gate electrode may be thought of as being located at the substrate side of the FET channel. The value of γ reflects modulation of V_b by the drain electrode. At low frequency, this modulation is governed by a redistribution of the (trapped) charge in the substrate and may be represented by resistors as in the figure, and γ_{dc} provides a reasonable prediction of R_{ds}. Capacitive coupling dominates at higher frequencies, where γ_{ac} provides a better representation. The shift from ac to dc behavior occurs at frequencies near $1/2\pi R_{bd}C_{bd}$.

This model fits naturally to both the low- and high-frequency response limits, and the intermediate response is governed by RC relaxation. The resistors are large, on the order of ρ/w, where ρ is the substrate resistivity and w is the FET width. This resistance results in insignificant leakage currents for FET's biased below cutoff. The capacitances are small, on the order of ϵw, where ϵ is the dielectric constant of GaAs, and thus do not significantly load the circuit at high frequency. The relaxation time is on the order of the bulk substrate relaxation time, $\rho\epsilon$, which is in the microsecond range.

Although the drain voltage "pulls" V_b, the voltage remains close to V_s since observed values of γ are in the range of 0.03–0.05.

By including a voltage dependence of R_{db}, C_{db}, and γ, we can obtain a model which is fully symmetrical with respect to interchange of the source and drain. The model works with either polarity (as does the Statz model). Such a model is highly desirable since, for many circuits,[1] this polarity changes during operation.

A fuller development of the low-frequency modeling would go beyond the intended scope of this paper.

VI. Conclusion

The SPICE model described here fits the $I-V$ data for GaAs MESFET's with parameters that can be related to the physics of the device. The improved fit to $I-V$ curves results in a better fit of small-signal parameters over bias. The formulations of the current source equations lend themselves naturally to a technique for incorporation of R_{ds} changes with frequency, and a model which is symmetrical with respect to interchange of source and drain is described.

The improved performance is achieved by changing the form of the model equations rather than elaborating upon existing equations. This reformulation results in a model that is simpler, more accurate, and more intuitive than previously proposed models.

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