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A hybrid model of III-V FETs with accurate high-order derivatives

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Abstract: In this article, a hybrid model for the current-voltage (I-V) characteristic and its high-order derivatives of III-V FETs is presented. The proposed model divides the entire operating region into several sub-regions and chooses optimum models in each subregion. The artificial neural network (ANN) techniques are employed to smoothly link the boundaries. The validity of this model has been verified by comparing the measurement and modeled results of a GaAs pHEMT.

Keywords: transistor modeling, I-V modeling, high-order derivatives, pHEMT, artificial neural network (ANN)

Classification: Electron devices, circuits and modules

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1 Introduction

Nonlinear circuits are an essential part of modern RF/microwave systems and blocks, such as power amplifiers, oscillators, and mixers [1]. The success of nonlinear circuit designs requires accurate nonlinear transistor models [2, 3, 4, 5, 6], which are used to predict the gain, intermodulation distortion (IMD), generation of harmonics, etc. In the past few decades, several models for III-V FETs (e.g., Curtice model [7], Angelov model [8], EEHEMT1 model [9], etc.) have been popularly used to describe the nonlinear drain current (I_{ds}) behavior. However, in order to simulate the third-order intermodulation (IMD3) performances as well as harmonic power levels, at the output, not only the *I-V* characteristics but also their higher-order derivatives (at least up to third order) have to be modeled accurately (see, e.g., [2, 3] and references therein).

Over the past decades, many methods have been presented to model the *I-V* characteristics and their higher-order derivatives [3, 4, 5, 6, 10]. For example, artificial neural network (ANN) is a more accurate and faster method. But the parameters of ANN do not have physical significance, which is concerned by designers. Empirical models (e.g., Curtice, Angelov, EEHEMT1 and so forth), which need not be trained, by contract, have physical meaning, such as drain-source current, gate-source capacitance, gate-drain capacitance and so on [3, 4, 5, 6]. Unfortunately, the high-order derivatives of those empirical models, partic-

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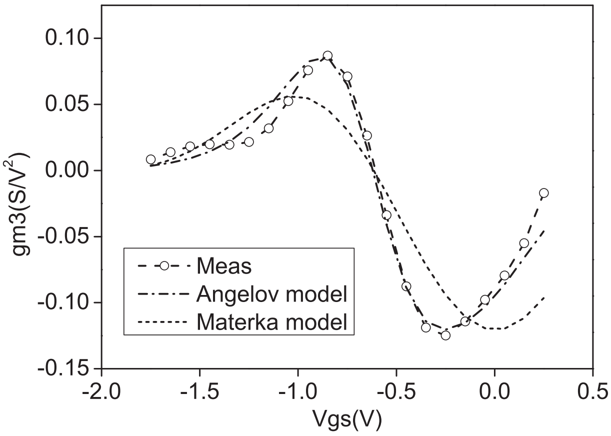

Fig. 1. Comparison between measured and modeled (based on "Angelov" type and "Curtice" type models) third-order derivative of I_{ds} at $V_{ds} = 3$ V.

ularly the third-order derivative, are not accurate enough to meet the requirements of the practical designs [4]. For instance, the "Curtice" type models (e.g., Materka [11], Statz [12], TOM3 [13] model, etc.) and "Angelov" type models are derivable, the accuracy of high-order derivatives of the I-V characteristics is not satisfactory (taking the third-order derivative for example as illustrated in Fig. 1). The "EE-HEMT1" type models employ a piecewise I_{ds} function with good accuracy in the entire operating region, however at the same time, with poor differentiability [3]. The poor differentiability is due to the unsmooth characteristic, which brought by the existence of boundaries between adjacent subregions. In order to overcome the above issues, this paper proposes a new model.

In this article, a hybrid model for III-V FETs with good accuracy of the I-V characteristics and high-order derivatives has been developed without losing the advantages of Curtice/Angelov-type and EEHEMT1 type models. Similar to EEHEMT1 model, the entire operating region is divided into several subregions, and the Curtice/Angelov-type models are used in each subregion. ANN techniques [10] have been employed to link the models at the boundaries between adjacent subregions, and such processing mode essentially guarantees the accuracy and the smoothness which benefits differentiability. As an example, the operating region of a GaAs pHEMT has been divided into four subregions to demonstrate the validity of this hybrid model. And compared to the traditional ANN, the parameters of this model have physical significance and most data of the model need not be trained.

2 Comparison of models for III-V FETS

In the past few years, numerous models have been developed to describe the characteristics of III-V FETs. The drain current equation for these models is typically based on the Curtice formulation, which has the form [6, 14]

$$I_{ds}(V_{gs}, V_{ds}) = f(V_{gs}) \times g(V_{ds}) \times \tanh(\alpha V_{ds}), \tag{1}$$

where $g(V_{ds}) \times \tanh(\alpha V_{ds})$ is used to model the drain voltage (V_{ds}) dependent characteristics. The hyperbolic tangent function provides a good description of the resistive behavior in the triode region (at low voltage in the vicinity of $V_{ds} = 0$) and

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the plateau behavior of the drain current in the saturation region (at high drain voltages). The function $f(V_{gs})$ is used to primarily depict the I_{ds}-V_{gs} (g_m-V_{gs}) relationship, which is crucial for the nonlinear performances of the devices.

Many modified models are on the basis of Curtice model, which has its notable advantages, but also, limitations. One limitation is that the existing models can hardly keep the high accuracy of *I*-*V* characteristics and their first three derivatives over the entire operating range. Specifically, the "Curtice" type models provide high accuracy in the subthreshold and saturation regions, but the modeling accuracy of intermediate region is often uncontrollable [3]. The "Angelov" type models employs a hyperbolic tangent function with different argument form. This improvement makes the "Angelov" type models more compact and differentiable to higher orders. As a result, this kind of models increases the accuracy of intermediate region, however, with the sacrifice of the accuracy near pinch-off or under open-channel state [6]. The "EEHEMT1" type model, as another type of model, has high accuracy in each subregion and a good description of the boundary condition. Nevertheless, the high-order differentiability of the EEHEMT1 model, in particular, the third order derivative can not meet the demands. All in all, existing models could not take into account all the above requirements at the same time.

3 Proposed hybrid model with accurate high-order derivatives

The developed hybrid model is the result of selecting and merging the appropriate widely-used models, and taking certain boundary conditions into consideration. The schematic of the proposed method is presented in Fig. 2, which consists of two main parts: the description of *I*-*V* characteristics as well as their derivatives in all subregions and the smooth link of boundaries between adjacent subregions. The following subsections provide details on the two parts of the hybrid model.

3.1 The description in different subregions

As shown in Fig. 2, the hybrid model employs a piecewise method to acquire high accuracy. In this model, the number of subregions is determined by the required accuracy. The I_{ds}-V_{gs} relationship in each subregion is modeled by a mathematical expression, which is similar to the EEHEMT1 model. However, the difference is that in different subregions the developed model chooses different existing models.

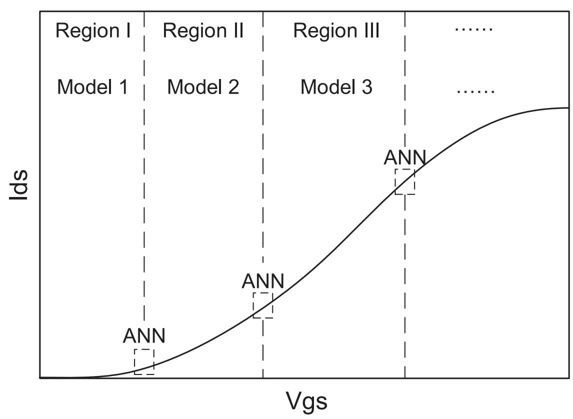

Fig. 2. The simplified schematic of the hybrid model.

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The basic selection criterion is to choose models with highest accuracy of *I-V* characteristics as well as their first three derivatives in each subregion. The accuracy of the hybrid model is guaranteed by extracting and optimizing the parameters of each chosen model in certain subregion. It should be noted that the same model can be used in different subregions, and the model parameters can be different if needed. To make an appropriate choice, the modelers should take full advantages of the existing models. Generally speaking, in the subthreshold and saturation regions "Curtice" type models are good choices, while in the intermediate region the "Angelov" type models should be considered as the preferred option.

3.2 The smooth link of boundaries using ANN techniques

Artificial neural network (ANN) techniques have been recognized as useful alternatives for device modeling especially for the description of nonlinear characteristics [15]. ANNs are able to approximate any nonlinear function and to learn from a known set of data. Multilayer perceptron (MLP), which is introduced in [16], is a frequently used neural network structure. Taking a three-layer perceptron for example, the first layer is the input layer, and the second layer is the hidden layer, and the third layer is the output layer, as indicated in Fig. 3. The process is done through a function called activation in the neuron, and the sum of processed information becomes the output of the neuron. By training and testing the neural network, smooth and good fitting output can be obtained.

However, having no information on the internal constitution of transistors, the predictive capability of ANN outside of training range is very poor [17]. For this reason, the ANN is used to link and smooth the boundaries between adjacent regions instead of describing the characteristics of transistors over the entire operating region, as illustrated in Fig. 2. The input information of an ANN structure may contain a physical parameter of a device/structure such as gate length and width of a field-effect transistor (FET) or electrical parameters such as voltage or current, depending on the application of the model. For DC models, we choose the gate-source voltage V_{gs} and the drain-source voltage V_{ds} as input vectors. Note that the input vectors are not measured data in this case, but the simulated data generated by the selected models in different subregions. The output information is the output current I_{ds} and its derivatives, respectively. The output near boundaries between adjacent subregions are formed by the ANN output results.

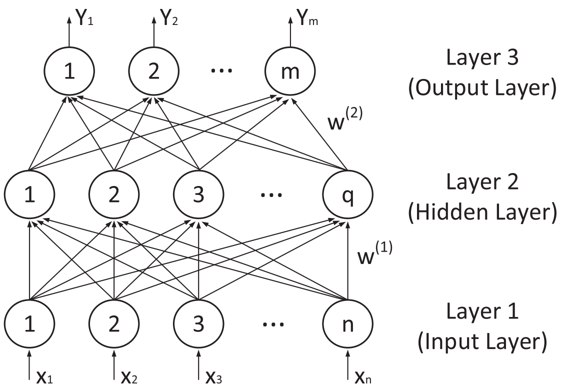

Fig. 3. A three-layer perceptron neural network structure.

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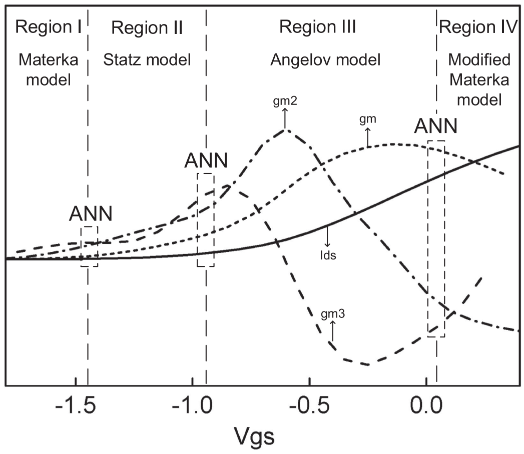

Fig. 4. The detailed schematic of the hybrid model.

4 Verification

A hybrid model for 0.25 µm gate lengths, 2 × 50 µm gatewidths GaAs pHEMT is developed to demonstrate the validity, as shown in Fig. 4. The pulsed *I-V* measurements are performed by the DIVA-265 dynamic *I-V* measurement system with 200 ns pulses separated by 1 ms. The measured multibiases of drain voltage V_{ds} is from 0 to 6 V with the step of 0.05 V and the gate voltage V_{gs} is from −1.8 to 0.45 V with the step of 0.05 V.

In this article, a four-segment model is taken as an example. As illustrated in Fig. 4, in the subthreshold region (region I) and saturation region (region IV), Materka and modified Materka models are used to acquire high accuracy. At the same time, the Statz model and Angelov model are selected in the quadratic region (region II) and the remaining intermediate region (region III), respectively. The model has been developed in a commercial Keysight Advanced Design System (ADS) circuit simulator. In addition, the smooth connections of boundaries with ANN is completed by using software NeutoModelerPlus_V2.1E with Quasi-Newton training method and 3 layers of Multilayer Perceptrons.

Comparison between the measurement and modeling data for the current and transconductance (the first-order derivative of I_{ds} with respect to the gate voltage) is shown in Fig. 5. Good agreement between the experimental and simulation data illustrates the validity of the proposed model. The effectiveness of the hybrid model is further verified through the comparisons of several nonlinear models with the second and third-order derivatives of I_{ds}, as shown in Fig. 6 and Fig. 7, respectively. It can be seen that the proposed model exhibits very high accuracy as well as smoothness over the entire operating region.

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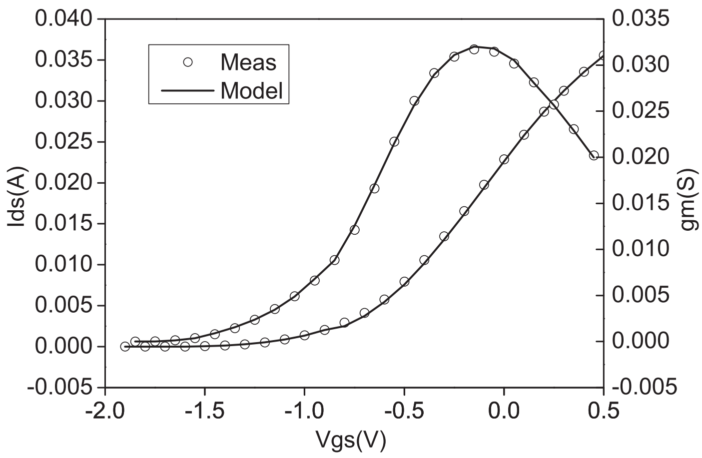

Fig. 5. Comparison between measured and modeled current and transconductance at $V_{ds} = 3\,\mathrm{V}$.

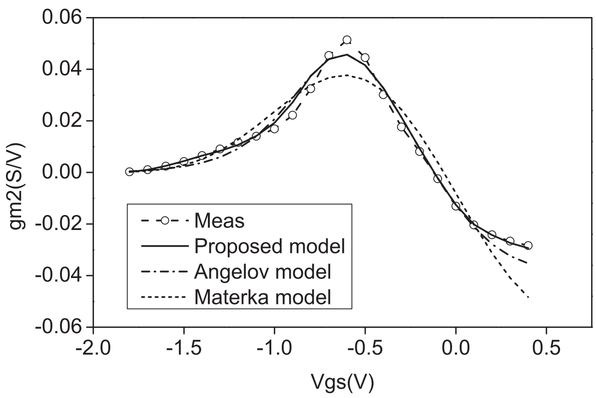

Fig. 6. Comparison between measured and modeled (based on "Curtice" type, "Angelov" type models and the hybrid model developed by the proposed method) second-order derivative of I_{ds} at $V_{ds} = 3\,\mathrm{V}$.

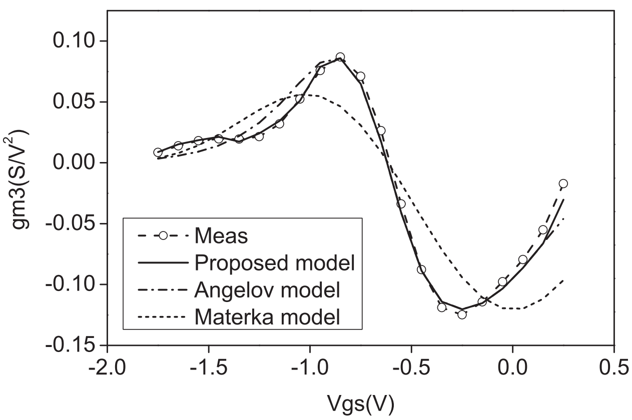

Fig. 7. Comparison between measured and modeled (based on "Curtice" type, "Angelov" type models and the hybrid model) third-order derivative of I_{ds} at $V_{ds} = 3\,\mathrm{V}$.

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5 Conclusion

A new hybrid model with accurate *I-V* characteristic and its first three derivatives for III-V FETs has been proposed. This hybrid model divides the entire operating region into several subregions. The number of the subregions is determined by the requirement of the accuracy for specific applications. Taking full advantage of the existing models, the developed model chooses different best-fit models with high accuracy of the *I-V* characteristics and their first three derivatives in each subregion. Moreover, the boundaries between adjacent subregions remain smooth connections by using ANN techniques. The proposed model can be also used to fit the higher-order (more than three) derivatives. Moreover, the essence of the proposed model can be extended to the further research on the small-signal *S*-parameter and large-signal modeling.

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