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journal or publication title: IEEE Microwave and Wireless Components Letters
volume: 27
number: 10
page range: 930-932
year: 2017
URL: http://id.nii.ac.jp/1438/00008804/
doi: 10.1109/LMWC.2017.2746678
GaN HEMT DC I-V Device Model for Accurate RF Rectifier Simulation

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Abstract—Recently, various high-efficiency RF rectifiers have been proposed. In this article, to improve the simulation accuracy of RF active rectifier circuits, a new device model for GaN HEMTs is proposed that improves the reproducibility of $I_D-V_{DS}$ characteristics in the third-quadrant region (both drain voltage and drain current are negative). Based on measured characteristic data of an actual GaN HEMT, the device parameters for this model have been decided, and the advantage of the new device model has been confirmed.

Index Terms—GaN HEMT, RF rectifier, device model, third-quadrant region.

I. INTRODUCTION

VARIOUS wireless power transmission systems have been proposed for several applications, such as remote sensing, wireless battery charging, and so on [1]–[3]. In recent years, various high-efficiency rectifiers using an active device such as a GaN HEMT have been proposed [4], [5]. Usually, such high-efficiency active rectifiers are designed using an RF circuit simulator. On the other hand, an active device in high-efficiency rectifiers works in the “third-quadrant” region, in which a reverse drain (or collector) voltage is applied and a reverse drain current flows. Especially, DC-to-RF/RF-to-DC interconversion systems [6] use both the first-quadrant and third-quadrant regions of an active device. However, such an operating mode of active devices is not seen in most other kinds of RF circuits, so simulation device models are considered to have insufficient reproducibility accuracy in the third-quadrant region. Raffo et al. [13] show that microwave intrinsic transistor characteristics can be expressed by nonlinear capacitive elements and nonlinear DC characteristics. In this letter, we attempt improving the DC characteristics of the device model, especially, third-quadrant region. It will improve the overall RF accuracy of the device model.

The look-up table approach [11] is a simple way to express nonlinear characteristics of active devices including third-quadrant region. In this approach, however, it is difficult to provide differentiable functions including higher order derivatives based on measured data. This is important problem to simulate high-efficiency rectifiers using harmonic treatment technique.

In this paper, first, the reproducibility accuracy of the EEHEMT1 device model on the third-quadrant region is shown by measuring and modeling for an actual GaN HEMT, then an improvement method for reproducibility is shown.

II. $I_D-V_{DS}$ CHARACTERISTICS EXPRESSION ON EEHEMT1 DEVICE MODEL

Keysight Technologies’ EEHEMT1 device model is one of the common simulation models for HEMT devices in the RF/Microwave field. Fig. 1 shows the internal equivalent circuit of the EEHEMT1 device model [7]. In Fig. 1, drain current $I_D$ is expressed some current sources. $I_{ds}$ generates a dominant DC drain current that depends on gate-source voltage $V_{GS}$ and drain-source voltage $V_{DS}$. $I_{gd}$ and $I_{gs}$ express the gate forward and breakdown currents, respectively. Though $I_{db}$, $R_{db}$, and $C_{bs}$ express the dispersion effects at low frequencies, it is not enough to express the complicated dispersion effects in GaN HEMTs [12]. Even so, at least more accurate DC model is needed to express these effects. In the EEHEMT1 device model, $I_{ds}'$, the no thermal effect version of $I_{ds}$, can be expressed by three terms, namely, $U$, $V$, and $W$, as follows:

$$
\begin{align*}
I_{ds}' &= U \cdot V \cdot W \\
U &= I_{ds}'\text{comp}(V_{GS}, V_{DS}) \\
V &= 1 + K_{APA} \cdot V_{DS} \\
W &= \tanh\left(\frac{3V_{DS}}{V_{SAT}}\right)
\end{align*}
$$

(1)

where $U$ or $I_{ds}'\text{comp}$ is a complicated function with respect to $V_{GS}$ and $V_{DS}$, $V$ is obviously a linear function with respect to $V_{DS}$, and $W$ represents the saturation effect of drain current by tanh function [8], [9]. Finally, $I_{ds}$ is derived from $I_{ds}'$ with taking the thermal effect, as shown by

$$
I_{ds} = \frac{I_{ds}'}{1 + \frac{P_{\text{diss}}}{PEFF}}
$$

(2)

where $P_{\text{diss}}$ is the power dissipation of the device due to $I_{ds}'$ and $V_{DS}$, and $PEFF$ is a device model parameter that determines the thermal effect of the device. The $I_{ds}$ must be a differentiable function, and its derivatives should ideally also be differentiable up to an infinite order. The $I_{ds}$ of the EEHEMT1 device model is described as a continuous function of at least 2nd order derivatives. Equation (1) is only used for
the first-quadrant region. For the third-quadrant region, the following equation is used instead of (2).

\[ I_{ds}(V_{DS < 0}) = -I_{ds}(V_{GS} - V_{DS}, -V_{DS}) \]  

(3)

Equation (3) expresses the \( I_D-V_{DS} \) characteristics in the third-quadrant region using the first-quadrant expression and the same device model parameters based on the terminal transformation technique with the device symmetry assumption, as shown by Fig. 2. This simple symmetry assumption provides a reasonable way to obtain the approximate characteristics in the third-quadrant region for most RF applications. However, in almost all actual FET devices such as GaN HEMTs, its structure is not symmetrical for improvement of the drain breakdown voltage [10]. This means that (3) does not give accurate characteristics in the third-quadrant region. Thus, for active RF rectifier simulation, more accurate device model is needed to provide more accurate characteristics in that region.

III. COMPARISON OF MEASURED CHARACTERISTICS AND EEHEMT1 DEVICE MODEL

In order to understand the reproducibility of the characteristics in the third-quadrant region, we measured the \( I_D-V_{DS} \) characteristics of an actual GaN HEMT device (WIN semiconductors’ 4×100μm gate width) based on stationary mode measurement. Then, we attempted to decide the parameters for the EEHEMT1 device model. As a result, it was impossible to fit the measured \( I_D-V_{DS} \) curves to the EEHEMT1 model in both the first-quadrant region and the third-quadrant region. The result of model fitting is shown in Fig. 3. In this result, the model and measured data in the third-quadrant region. The assumption of device symmetry is considered to be one of the reasons for this difference. To improve this mismatch, we introduced a new function named \( V' \) instead of \( V \) in (1).

\[ V' = 1 + KAPA \cdot V_{DS} + \frac{1}{A \cdot (PHI - V_{GS})^{B+D \cdot V_{DS}}} \cdot \tanh\left(\frac{V_{DS}}{C} - 1\right) \]  

(4)

This equation corrects the \( I_{ds} \) in the third-quadrant region for better approximation, but there is almost no effect on other regions. In (4), each \( A, B, \) and \( D \) is the parameter that determines the influence of \( V_{DS} \) on \( I_{ds} \). \( C \) is the roll-off factor of \( V' \) around \( V_{DS} = 0 \). A small offset \( PHI \) prevents the divergence of \( V' \) on \( V_{GS} \geq 0 \). In addition, in (4) the device symmetry assumption expressed as (3) is not applied. In other words, each \( V_{GS} \) and \( V_{DS} \) in (4) means the actual gate and drain voltage, respectively, even in the third-quadrant region. A comparison example between \( V \) and \( V' \) is shown in Fig. 4. Equation (4) is a differentiable function with respect to \( V_{GS} \) and \( V_{DS} \) with \( V_{GS} < PHI \), and at least 2nd order derivatives are also differentiable with \( V_{GS} < PHI \), as shown in the following equation:

\[ \frac{\partial V'}{\partial V_{DS}} = KAPA + \frac{1}{AC(PHI - V_{GS})^{B+D \cdot V_{DS}}} \cdot \left\{ 1 - \tanh^2\left(\frac{V_{DS}}{C} - 1\right) \right\} \]  

(5)

\[ \frac{\partial^2 V'}{\partial V_{DS}^2} = - \frac{2}{AC^2(PHI - V_{GS})^{B+D \cdot V_{DS}}} \cdot \tanh\left(\frac{V_{DS}}{C} - 1\right) \left\{ 1 - \tanh^2\left(\frac{V_{DS}}{C} - 1\right) \right\} \]  

(6)

\[ \frac{\partial V'}{\partial V_{GS}} = - \frac{1}{A(PHI - V_{GS})^{B+D \cdot V_{DS}}} \cdot \left\{ D \cdot \ln(PHI - V_{GS}) - B + D \cdot V_{DS} \right\} \cdot \tanh\left(\frac{V_{DS}}{C} - 1\right) \]  

(7)

\[ \frac{\partial^2 V'}{\partial V_{GS}^2} = - \frac{1}{A(PHI - V_{GS})^{B+D \cdot V_{DS}}} \left\{ \left\{ D \cdot \ln(PHI - V_{GS}) - B + D \cdot V_{DS} \right\}^2 + \frac{B + D \cdot V_{DS}}{(PHI - V_{GS})^2 + D^2} \right\} \cdot \tanh\left(\frac{V_{DS}}{C} - 1\right) \]  

(8)

IV. FITTING RESULT USING THE IMPROVED MODEL

Using \( V' \) instead of \( V \) in (1), we produced an improved version of the EEHEMT1 device model. The fitting result for

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**Fig. 2.** Transform the third-quadrant region to first-quadrant region.

**Fig. 3.** Measured \( I_D-V_{DS} \), simulation result using EEHEMT1 model, and model parameters.

**Fig. 4.** Plot example for \( V \) and \( V' \) respectively.
the actual device which is described in section III, is shown in Fig. 5.

Fig. 5. Measured $I_D$-$V_{DS}$ simulation result using the improved model, and model parameters.

The improved device model gives good approximation in the third-quadrant region without a large effect in the first-quadrant region. This would be helpful in the design of high-efficiency active rectifiers.

V. CONCLUSION

We described the reproducibility of the EEHEMT1 device model in the third-quadrant region, and proposed an improved device model. The improved device model gives better $I_D$-$V_{DS}$ curves in the third-quadrant region without much effect in the first-quadrant region. This would be helpful in the design of high-efficiency active rectifiers.

REFERENCES