An Accurate I-V Model of Gan HEMT Power Device for the Application of Low Atmospheric Pressure

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AN ACCURATE I-V MODEL OF GAN HEMT POWER DEVICE FOR THE APPLICATION OF LOW ATMOSPHERIC PRESSURE

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Abstract—The characteristic variation of GaN HEMT device under low atmosphere pressure is studied in this research, which is a new challenge in the future. However, the variation is so small that cannot be represented by common current models. An accurate nonlinear current model is proposed in this study based on Angelov model to fit the small differences. The comparisons of simulated results based on the improved current model and measured results show that the improved model is accurate enough to describe the small differences and can improve the accuracy of nonlinear model of GaN HEMT device.

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1. INTRODUCTION

Recently AlGaN/GaN HEMT is emerging as a frequently employed technology in airborne and aerospace devices due to high power density, high power added efficiency and resistance to radiation [1]. More and more AlGaN/GaN HEMT devices have been used in satellite and aerospace equipments. An accurate large signal equivalent circuit model is crucial for the designs and applications of GaN HEMT devices. The performances of GaN HEMT devices have small variations under low atmosphere pressure compared with normal condition. Although the differences between the two atmosphere pressure (AP) conditions are small, the variations will be very crucial in some cases due to the space environment. There have already been many equivalent circuits and methods to model GaN HEMT device. However, the common nonlinear current models could not represent the small different performances due to lacking accuracy. An improved drain to source current (I_{ds}) model based on Angelov one is proposed in this paper to resolve the problem. The improved I_{ds} model can not only describe the self-heating effect but also represent the small different performances between the two AP conditions because of high accuracy of the model. A GaN HEMT power device was measured under two AP conditions (1 atm and 0.15 atm) and modeled by using the improved I_{ds} model based on the test data. The comparisons of the simulated and measured results show that the I_{ds} model proposed in this study can improve the accuracy of nonlinear model of the GaN HEMT power device as well as the self-heating effect, and the small different performances can both be represented by using the current model.

This paper is organized as follows: In Section 2, the small differences under the two AP conditions are shown, and the inducements are analyzed. The improved I_{ds} model is proposed and practically verified in Section 3. The conclusion is given in Section 4.

2. THE CHARACTERISTIC VARIATIONS AND CAUSING ANALYSIS

The operating current of a GaN HEMT power device was measured under two identical conditions except AP (1 atm and 0.15 atm). Some small differences are observed and extracted from the compared results as shown in Fig. 1.

In the figure above, V_{ds} and V_{gs} are voltages of drain to source and gate to source respectively. From the I-V curves, it can be seen that the I_{ds} decreases when the V_{ds} and V_{gs} are large enough, and the

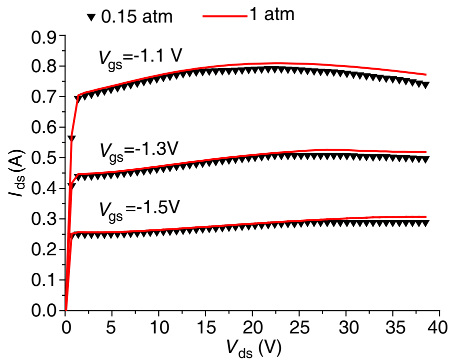


Figure 1. The comparisons of measured I_{ds} between two AP conditions.

inducement is known as self-heating effect. However, the decreasing margins are not identical between the two testing AP conditions. The differences may be caused by reasons as follows:

- difference of thermal conduction

As a thermal conductive medium, air plays a significant role in heat transfer [14]. The equation of state of the ideal gas is described as bellow [2]:

$$\rho = \frac{m}{V} = \frac{P}{R_g T} \tag{1}$$

where ρ, m, V, T, P and R_g represent air density, air mass, air volume, temperature, atmosphere pressure and gas constant, respectively. The equation of thermal conduction is described as follow [3]:

$$Q = \frac{K \times A \times \Delta T \times \Delta t}{D} \tag{2}$$

where Q is the quantity of heat transfer. $K, A, \Delta T, \Delta t$ and D represent thermal conductivity, contact area, temperature difference, conductive time and distance, respectively. And the gas thermal conductivity K can be calculated by the following equation.

$$K = \frac{1}{3}\rho v \lambda \frac{C_m}{M_m} \tag{3}$$

where $\rho, v\lambda, C_m$ and M_m represent gas density, gas momentum, molar heat capacity and molar mass.

From the three equations above, a direct proportion can be obtained as follows:

$$Q \propto K \propto \rho \propto P \tag{4}$$

It can be seen that low atmospheric pressure will dramatically decrease the conductive heat originated from the GaN HEMT power device.

- variations of surface resistivity

The surface resistivity is usually defined by test. According to measured result, the surface resistivity will increase a little with the fall of the atmospheric pressure [4, 13]. Although the variation is very small, the surface resistance of the electrodes will increase a little, which is another possible reason causing I_{ds} to decrease.

- other inducements

The variation of current may be also caused by deformation, change of dielectric constant and other reasons [5].

3. THE IMPROVED CURRENT MODEL AND PRACTICAL VALIDATION

In order to describe the small variation, an improved current model based on Angelov one [6, 7] is proposed in this study. The improved model can not only describe the self-heating effect but also fit the different bending margins of the I_{ds} curves by adjusting fitting factors.

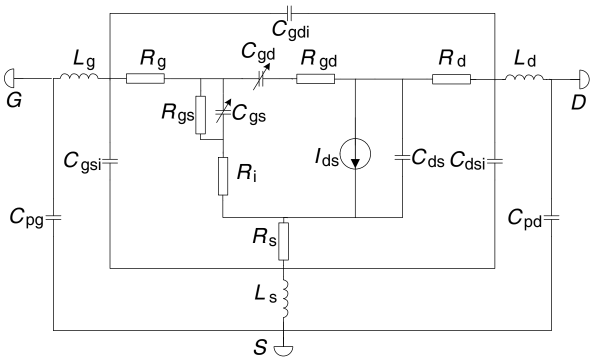


Figure 2. Typical equivalent circuit model of GaN HEMT device.

Figure 2 shows a common AlGaN/GaN HEMT large signal equivalent circuit topology. Typically, the most significant nonlinear equivalent element is I_{ds}. The improved I_{ds} model is presented as follows:

$$I_{ds} = I_{pk}(1+\tanh(f_1))(1+f_2V_{ds})\tanh(DV_{ds}) \tag{5}$$

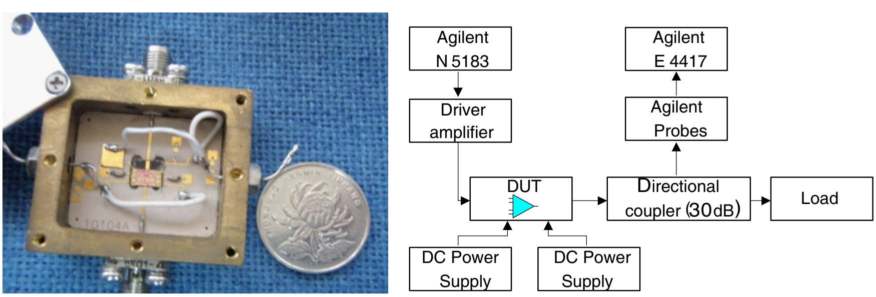
$$f_1 = p_1(V_{gs}-v_{pk})+p_2(V_{gs}-v_{pk})^2+p_3(V_{gs}-v_{pk})^3 \tag{6}$$

$$
\begin{aligned}
I_{pk} &= \frac{I_{pk0}}{A(V_{ds}^{p}V_{gs}^{q}) + BV_{ds}^{0.6V_{gs}} + C} &(7)\\
v_{pk} &= F + GV_{ds} &(8)\\
f_2 &= H\exp(M\left|V_{gs}\right|^{Q}) &(9)
\end{aligned}
$$

where I_{pk} and V_{pk} are the current and voltage of drain to source respectively when maximum transconductance is obtained; $A, B, C, D, H, Q, M, p_1, p_2$, and p_3 are constants for fitting; F and G are used to describe the V_{ds} effect on knee voltage caused by short-channel effects. Compared with original model, the greatest improvement is the expression of I_{pk}, in which a new denominator is used. The model with the improvements can accurately fit different decline margins of I_{ds} in saturation under different testing conditions by changing the fitting parameters.

The parameters of the GaN HEMT power device (such as operating current and small signal S-parameters) were measured and modeled for verifying purpose as shown in Fig. 3. The thickness of the silicon carbide (SiC) substrate of the device is 150 µm. The T shape gate is made from Ni/Au with 0.5 µm width. The SiNx is used as passivation and encapsulation layer. The GaN device contains 24 cells, and the chip was emplaced on Cu-Mo-Cu laminate with about 43 dBm output power at 1-dB compression point. The quiescent operation point was $V_{ds} = 28\,\text{V}$ and $V_{gs} = -1.5\,\text{V}$ with about 255 mA drain to source current. The maximum efficiency was about 60%. The test platform was used to measure the characteristics of the power amplifier. The single chip size was 7.2mm × 4.2 mm.

The I_{ds} of the GaN HEMT power device was measured in two different AP conditions with varying bias voltages. The current curves were fitted respectively based on the measured results for the two AP

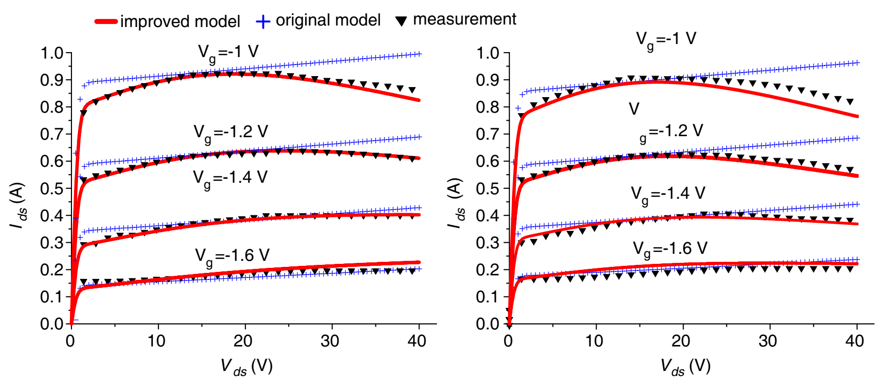


(a) (b)

Figure 3. (a) The power amplifier for validation. (b) Measurement setup for power amplifier.

conditions. The comparisons of simulated results and measured data are shown in Fig. 4. The value of each parameter is listed in Table 1.

It can be seen that the differences between the two AP conditions are so small that the original Angelov model cannot represent them. The compared results show that the improved current model can both describe the self-heating effect and fit the small *I-V* variations of GaN HEMT power device under the two different AP conditions well. Advanced Design System 2009 (ADS2009) was used as the basic simulating software in this study. The improved current model was implemented in ADS 2009 by using symbolic defined devices (SDD). With the help of accurate small signal equivalent circuit model [8], the values of parasitic parameters and linear equivalent elements which are identical under the two AP conditions were extracted from measured



(a) (1 atm) (b) (0.15 atm)

Figure 4. The compared results of simulated and measured I_{ds} under the two AP conditions. (a) is 1 atm, (b) is 0.15 atm.

Table 1. The numerical values of the *I-V* modeling parameters extracted under two AP conditions.

	A	B	C	F	G	H	M	I_{pk0}
1 atm	$7.00e-4$	$-4.12e-2$	1.03	1.46	$-6.67e-3$	$2.04e-2$	$1.33e-1$	1.50
0.15 atm	$6.99e-4$	$-4.12e-2$	1.03	1.30	$-6.04e-3$	$2.68e-2$	$1.33e-1$	1.90
	Q	p	q	p_1	p_2	p_3	D	
1 atm	$9.49e-2$	2.10	$1.47e-1$	$-3.48e-1$	$1.11e-1$	$1.25e-1$	1.61	
0.15 atm	$9.49e-2$	2.17	$1.08e-1$	$-1.19e-1$	$7.45e-2$	$1.00e-1$	1.60	

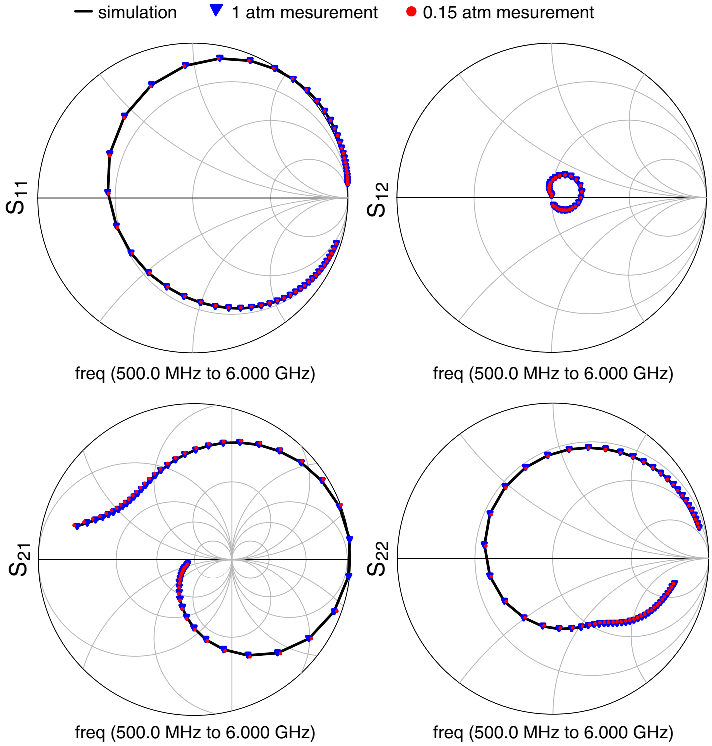


Figure 5. Simulated small S-parameters and measurements under the two AP conditions (0.5–6 GHz).

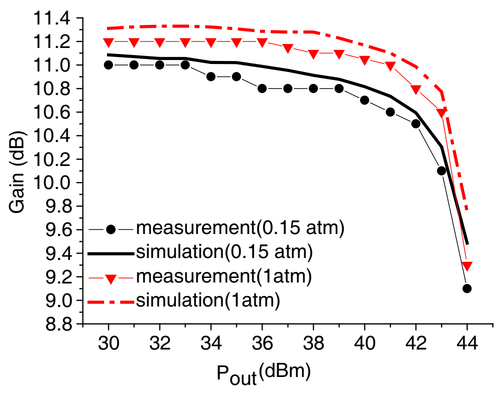
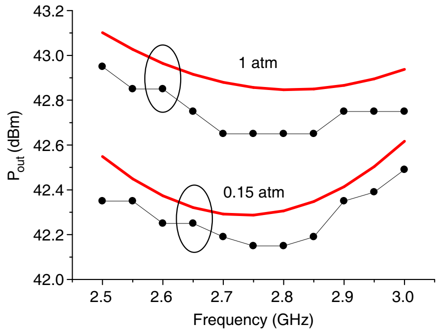
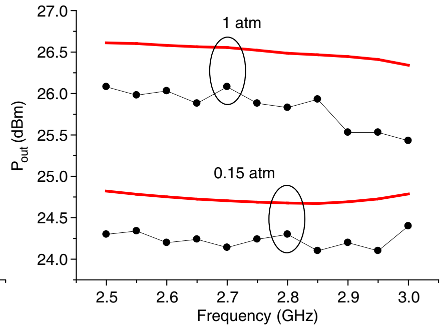


Figure 6. The comparisons of simulating gains and measurements under the two AP conditions ($f = 3$ GHz).



(a) $1f_0$ fundamental wave



(b) $2f_0$ second-harmonic wave

Figure 7. The compared results of simulating harmonic performances and measurements under the two AP conditions. ($P_{in} = 32\,\text{dBm}$).

small signal scattering (S) parameters as shown in Fig. 5. The output characteristics of the GaN HEMT power device based on simulation and measurement are compared in Fig. 6 and Fig. 7 [9–12, 15]. The DC bias voltages are set as follows: $V_{gs} = -1.5\,\text{V}$; $V_{ds} = 28\,\text{V}$.

The comparisons in the figures above show that the small different performances between the two AP conditions can be represented well by using the improved I-V model proposed in this paper.

4. CONCLUSION

In order to describe the small variation of I_{ds} between different AP conditions, an improved nonlinear current model based on Angelov model is proposed in this paper. The differences, although very small between the two different AP conditions, can be represented due to the high accuracy of the improved model, and the self-heating effect can also be described well. The current model is easy to be implemented in commercial software and can improve the accuracy of large signal equivalent circuit model of GaN HEMT power device dramatically through the practical verification.

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