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A CAD oriented quasi-analytical large-signal drain current model for 4H-SiC MESFETs*

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This paper reports that a 4H-SiC MESFET (Metal Semiconductor Field Effect Transistor) large signal drain current model based on physical expressions has been developed to be used in CAD tools. The form of drain current model is based on semi-empirical MESFET model, and all parameters in this model are determined by physical parameters of 4H-SiC MESFET. The verification of the present model embedded in CAD tools is made, which shows a good agreement with measured data of large signal DC *I-V* characteristics, PAE (power added efficiency), output power and gain.

Keywords: 4H-SiC MESFET, drain current model, CAD, large signal
PACC: 5270G, 7210, 73330, 7360F

1. Introduction

The MESFET (Metal Semiconductor Field Effect Transistor) based on 4H-SiC is increasing awareness of the advantages of high power density, high thermal conductivity and broad bandwidth applied to RF (radio frequency) and MW (microwave) power circuits. The potential wide application of RF power circuit provides an impetus for the research of 4H-SiC MESFET large signal modelling. The large signal drain current model is one of the key problems in the modelling of 4H-SiC MESFET, which provides the basic DC *I-V* characteristics and strongly determines the gain and power dissipation parameters of a transistor.

Some previous works about modelling the 4H-SiC MESFET large signal drain current are made. The table-based model[1] and empirical model[2] are strongly dependent on measured data and these make them difficult to predict the performance when device structure is modified. The analytical models developed by Yang,[3] Sankha[4] and Murray[5] cannot be implemented to CAD tools directly due to the implicit function or complexity in the expressions. Also the numerical model[6] cannot be applied to commercial CAD tools directly.

An improved physical-based and semi-empirical-like 4H-SiC MESFET large signal drain current model is proposed in this paper and all parameters in this model are based on the structure and physical parameters of 4H-SiC MESFET. In addition, it can be directly implemented in the commercial RF and MW circuit CAD tools, such as advanced design system (ADS) Ansoft Designer, etc.

2. Drain current model

The large-signal equivalent circuit of 4H-SiC MESFET is shown in Fig.1. The circuit includes two parts: one part of the external or parasitic elements is independent on the biasing conditions, the other part within the dotted line box in this figure of the intrinsic elements (I_{DS}, I_{GD}, I_{GS}, C_{GD}, C_{GS}, C_{DS} and R_i) is dependent on the biasing conditions.

Parasitic elements and gate current parameters can be extracted by using the cold FET bias measurements, and nonlinear capacitance parameters by high frequency small signal measurements. Here, the drain current model is discussed and the parasitic elements and capacitance elements are beyond the scope.

An improved drain-source current model is proposed based on physical expression referred to the Materka GaAs FET model.[7] To verify the present model embedded in ADS, the Schottky junction gate current model and semi-empirical nonlinear capacitance model are also used.

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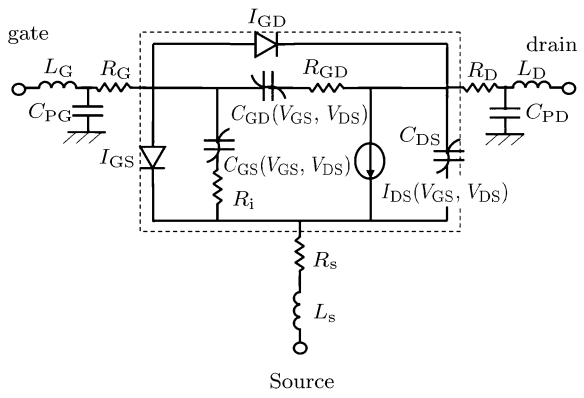


Fig.1. 4H-SiC MESFET large-signal equivalent circuit.

The expression of the 4H-SiC MESFET DC drain-source current is described as follows:

$$I_{DS} = I_{DSS0} \times \left(1 - \frac{V_{GS}}{V_T}\right)^2 \times [1 + \lambda V_{DS}] \times \tanh(\alpha V_{DS}), \quad V_{GS} \geq V_T, \tag{1a}$$

$$I_{DS} = 0, \quad V_{GS} < V_T, \tag{1b}$$

where I_{DSS0} is the linearly extrapolative drain-source saturation current value at $V_{GS} = 0$ (see Fig.2), α is the hyperbolic tangent function coefficient to describe the behaviour of the curves of I_{DS}–V_{DS}, λ is the channel length modulation coefficient, V_T is the threshold voltage ($V_T = V_{bi} - V_P$, where V_{bi} is the built-in voltage, V_P is pinch-off voltage). The definitions of the parameters α, λ are the same as Statz–Raytheon model.[8]

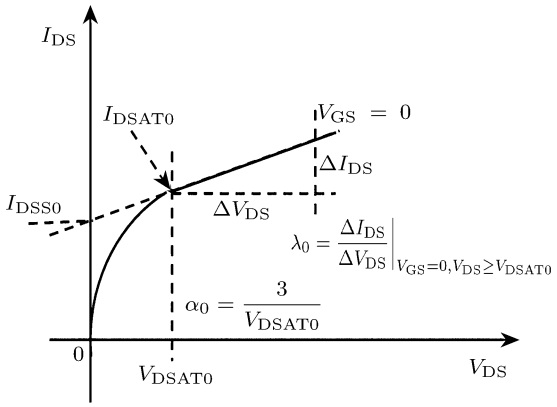


Fig.2. Sketch map of parameters in calculation of I_{DSS0}.

The difference between the present model and Materka model lies in α and λ which vary with V_{GS} in our model while keep constant in Materka model once extracted from measured data. This modification leads to a better accuracy to model the drain current. And all the parameters in our model are only calculated once, avoiding the iterative solution of the parameters in every gate and drain bias,[3−5] which limited their applications in CAD tools.

A) I_{DSS0}

For the n-type channel MESFET, I_{DSS0} can be determined by

$$I_{DSS0} = \frac{I_{DSAT0}}{1 + \lambda_0 V_{DSAT0}}, \tag{2}$$

where I_{DSAT0}, λ_0 and V_{DSAT0} are drain-source saturation current, channel length modulation coefficient and saturation voltage at $V_{GS} = 0$ respectively. Here, $V_{DSAT0} = \dfrac{3}{\lambda_0}$, α_0 and λ_0 can be obtained in the following section. I_{DSAT0} is expressed by[9]

$$I_{DSAT0} = \frac{3 I_P (1 - u_{m0})}{Z}, \tag{3}$$

where I_P is the pinch-off current, u_{m0} is the normalized width of depletion layer at $V_{GS} = 0$, which can be obtained from Refs.[9,10], Z is the ratio of the linearly extrapolative low-field drift velocity to saturation drift velocity, and

$$Z = \frac{u_{n0} V_P}{v_{sat} L}, \tag{4}$$

where u_{n0}, v_{sat} are the low-field electron mobility and the saturation electron drift velocity of 4H-SiC respectively, L is the channel length of 4H-SiC MESFET.

B) α

Due to the influence of field dependent mobility of SiC and the short channel effect,[11] the saturation voltage coefficient α varies with the gate applied voltage. For the sake of easier operation in CAD tools, the expression of α is defined as

$$\alpha = \alpha_0 \times \left(1 - \frac{V_{GS}}{V_T}\right), \tag{5}$$

where α_0 is the saturation voltage coefficient at $V_{GS} = 0$ in terms of the assumption of gradual channel approximation for 4H-SiC MESFET, and the expression of α_0 given in Ref.[12] is as follows:

$$\alpha_0 = \frac{V_P + 3E_S \left[L - \frac{2a}{\pi} \sinh^{-1}\left(\frac{\pi K_d}{2aE_S}\right)\right]}{E_S L \left(1 - \sqrt{\frac{E_S L}{V_P + E_S L}}\right)(V_P + 3E_S L)}, \tag{6}$$

where K_d is the domain parameter which is introduced by Ref.[13], E_S is electric field value at the electron drift velocity saturation, W, a are channel width and depth of 4H-SiC MESFET under the gate respectively.

C) λ

For the short channel effects such as DIBL (drain induced barrier lowering) and threshold voltage shift,[11,14] output conductance of 4H-SiC MESFET increases with the gate applied voltage. Hence, λ can be modified by:

$$\lambda = \lambda_0 - \frac{V_{\rm GS}}{2 \times V_{\rm P}^2}, \tag{7}$$

where λ_0 is the channel length modulation coefficient at $V_{\rm gs} = 0$ in terms of the assumption of gradual channel approximation for 4H-SiC MESFET, the second term shows the variation of λ with $V_{\rm GS}$. λ_0 is given by Ref.[12]

$$\lambda_0 = \frac{\frac{V_{\rm P}+3E_{\rm S}(L-L_{\rm SAT})}{V_{\rm P}+3E_{\rm S}\left[L-L_{\rm S}(2V_{\rm P}+\frac{E_{\rm S}L}{1+\xi},V_{\rm bi})\right]}-1}{2V_{\rm P}+\frac{E_{\rm S}L}{1+\xi}}, \tag{8}$$

where ξ is the saturation index,[12] $L_{\rm SAT}$ and $L_{\rm S}(V_{\rm DS}, V_{\rm GS})$ are given in Ref.[12].

3. Simulation result and verification

A verification of this drain current model is made through the 4H-SiC MESFET characteristics that Siriex reported.[1] The physical parameters and obtained parameters are listed in Table 1 and Table 2 respectively. During calculation, the incomplete ionization[15] of 4H-SiC, a very important factor which is different from the GaAs- and Si-based devices, has been taken into account, and $N_{\rm D}^+$ is obtained by approximately first level ionization for the freezing effect of SiC material.[3] To evaluate $V_{\rm P}$, the offset of short channel of MESFET is also considered.[10]

Table 1.

$E_{\rm S}/10^5$(V/cm)	3.05	W/μm	2000
$V_{\rm T}$/V	−11	L/μm	0.7
$v_{\rm sat}/10^7$(cm/s)	2	a/μm	0.25
ξ	0.15	$N_{\rm D}^+/10^{17}{\rm cm}^{-3}$	1.16
$K_{\rm d}$	1.0	$\mu_{\rm n0}$/(cm/V·s)	546

Table 2.

α_0/(1/V)	0.233
λ_0/(1/V)	0.0195
$I_{\rm DSS0}$/mA	234

Figure 3 shows the comparison of measured and simulated results of the DC I-V characteristics of drain-source current. From this figure, very good agreement between the modelled and measured data is observed.

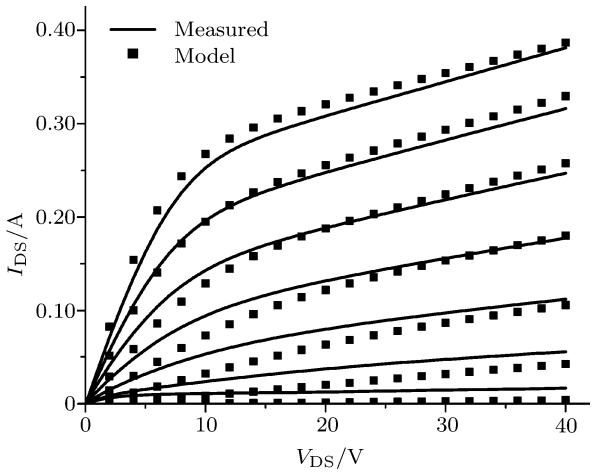


Fig.3. Measured and Simulated DC I-V Characteristics of drain-source current $I_{\rm DS}$.

This model has been embedded in CAD tool ADS. In order to verify the model by evaluating the RF performance of 4H-SiC MESFET, Chalmer's nonlinear capacitance model[16] and Schottky junction gate current model[8] are also used.

The measured data of this verification is obtained from Ref.[1]: parasitic elements are cited directly, and the capacitance parameters of Chalmer's model, listed in Table 3, are extracted based on the data present in Ref.[1]. The reverse saturation current of Schottky gate current model is assumed as 5 mA and the ideality factor is 2.

Table 3.

$C_{\rm GS0}$/pF	0.55	M_1	−0.1	M_3	−0.1
$C_{\rm GD0}$/pF	0.45	M_2	−0.008	M_4	0.035

A comparison of the simulation results and the measured data[1] of output power, PAE(power added efficiency) and gain is shown in Figs.4–6. The bias is $V_{\rm DS} = 20$ V, $I_{\rm DS} = 80$ mA, the operational frequency is 1.8 GHz, and the simulated input and output impendence are 23.5−74j and 40+53j respectively. We can see from the comparisons that simulation results match the experiment data very well.

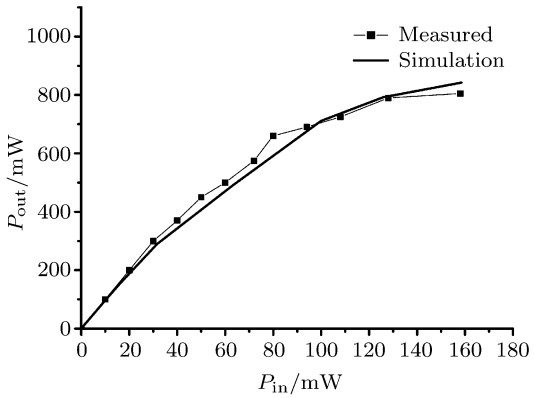


Fig.4. Measured and simulated of output power at bias of $V_{DS} = 20\,V$, $I_{DS} = 80\,mA$, Freq=1.8 GHz.

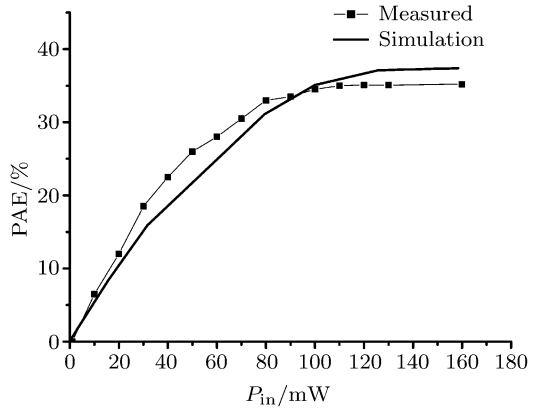


Fig.5. Measured and simulated of PAE at bias of $V_{DS} = 20\,V$, $I_{DS} = 80\,mA$, Freq=1.8 GHz.

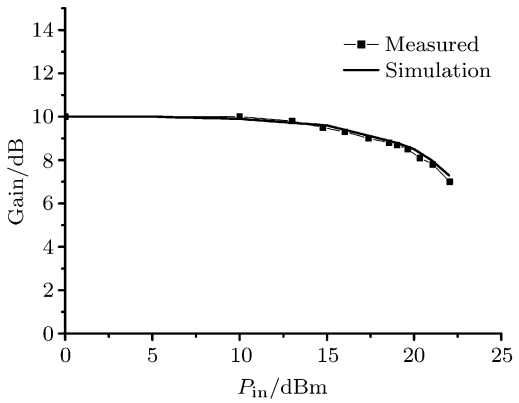


Fig.6. Measured and simulated of gain at bias of $V_{DS} = 20\,V$, $I_{DS} = 80\,nA$, Freq=1.8 GHz.

4. Conclusion

A quasi-analytical drain current model for 4H-SiC MESFETs is developed by considering the physical structure of device and easier implementation with CAD tools. Using this model, one can predict the RF performance of 4H-SiC MESFET in terms of the physical parameters. Simulation results in this paper show that quite good agreement is achieved and the execution with the presented model embedded in ADS is efficient. In addition, this model can serve as a starting point to improve the simplification of the large-signal parameter extraction procedure.

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