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A new physics-based self-heating effect model for 4H-SiC MESFETs*

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A new self-heating effect model for 4H-SiC MESFETs is proposed based on a combination of an analytical and a computer aided design (CAD) oriented drain current model. The circuit oriented expressions of 4H-SiC low-field electron mobility and incomplete ionization rate, which are related to temperature, are presented in this model, which are used to estimate the self-heating effect of 4H-SiC MESFETs. The verification of the present model is made, and the good agreement between simulated results and measured data of DC $I-V$ curves with the self-heating effect is obtained.

Keywords: 4H silicon carbide, metal semiconductor field effect transistor, self-heating effect, computer aided design

PACC: 7210, 7220, 73330, 7360F

1. Introduction

The SiC metal semiconductor field effect transistor (MESFET) is considered as one of the potential important devices of the next generation for the applications of high power, compact, high frequency and high efficiency radio frequency (RF) and microwave electric circuits, especially monolithic microwave integrated circuits (MMICs),[1−5] such as new generation phased array radar, base station, and satellite and aerospace based systems. 4H-SiC RF and microwave power MESFET is the most attractive transistor among the polytypes 3C, 6H, 4H-SiC MESFET.[6]

Self-heating effect has been realized to be an important research topic in power devices usually. The ideal thermal conductivity of 4H-SiC is 4.9 W/cm.K at 300 K, which causes the device performances of 4H-SiC MESFET to be less influenced by the self-heating effect than those of Si- and GaAs-based devices under the same power dissipation.[7−9] However, as investigated before,[7,10] the self-heating effect is still one of the crucial issues in 4H-SiC MESFETs.

There are several factors that are responsible for the self-heating effect of 4H-SiC MESFETs. Firstly, the device power density achieved now is in a range from 2 to more than 7.8 W/mm which is much higher than those in previous similar structures based on silicon, gallium and compound semiconductors,[9−11] and the efficiencies of large devices are still restricted. Secondly, the thermal conductivity of 4H silicon carbide reduces exponentially as the ambient temperature increases, and the ideal value (4.9 W/cm · K at 300 K) of 4H silicon carbide thermal conductivity cannot be reached usually due to specific semiconductor processing technology.

Some previous studies of modelling the self-heating effect in 4H-SiC MESFETs have been performed. Liu *et al*[9] investigated the thermal issues with the numerical model. Royet *et al*[10] and Yang *et al*[11] developed the analytical models to describe the self-heating effects. The numerical and the analytical models well described the self-heating principle, but they could not be used in the CAD tools in most cases. The iteration steps to calculate $I-V$ curves in the analytical models[10,11] restricted their further applications. Thus, a CAD oriented and accurate model to describe self-heating effects has especially emphasized driving the radio frequency integrity circuit (RFIC) design of 4H-SiC MESFETs.

In this paper, a CAD oriented self-heating effect

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model for 4H-SiC MESFETs is presented. Firstly, we give a brief derivative by combining an analytical model and a CAD-oriented quasi-analytical drain current model of 4H-SiC MESFETs. Secondly, we present a relationship between the main parameters and temperature for the circuit oriented design, thereby obtaining a complete expression of self-heating effect model for 4H-SiC MESFETs. And finally the presented model is verified and discussed.

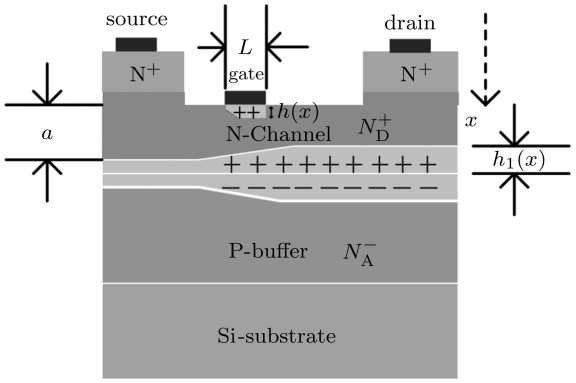


Fig.1. Cross section of 4H-SiC MESFET.

2. Model descriptions

The approach presented here is based on a quasi-analytical drain current model of 4H-SiC MESFETs, which was published in Ref.[12]. A circuit oriented self-heating effect model is derived based on the physical principle of device and the presented quasi-analytical drain current model.

2.1. Drain current model incorporated into self-heating model

The cross-section of the n-channel 4H-SiC MESFET is shown in Fig.1. The ohmic contacts are made at the terminals of drain and source, the gate with the recessed structure is formed on n-type SiC channel with a Schottky contact, and the low p-type doping layer and SiC substrate are underneath the channel sequentially.

For the n-type channel, the channel current for 4H-SiC MESFET can be given as[8]

$$I_{\mathrm{DS0}} = qWN_{\mathrm{D}}^{+}\mu_0 \left\{ \frac{1}{1+\dfrac{\mu_0 E}{v_{\mathrm{sat}}}} E\left[a-h(x)-h_1(x)\right] \right\}, \quad (1)$$

where q is the electron charge, W is the width of MESFET channel, N_{D}^{+} is the ionization doping density, and μ_0 is the low field electron mobility, E is the lateral electric field under the channel, v_{sat} is the electron saturation velocity, a is the channel thickness, $h(x)$ represents the depletion layer controlled by gate applied voltage, and $h_1(x)$ is the height of depletion region at the interface of channel/ buffer layer at a distance of x.

Now, we introduce a CAD orient and quasi-analytical drain current model as follows:[12]

$$I_{\mathrm{DS0}} = I_{\mathrm{DSS0}} \times \left(1-\frac{V_{\mathrm{GS}}}{V_{\mathrm{T}}}\right)^2 \times [1+\lambda(V_{\mathrm{GS}})V_{\mathrm{DS}}] \times \tanh[\alpha(V_{\mathrm{GS}})V_{\mathrm{DS}}], \quad V_{\mathrm{GS}} > V_{\mathrm{T}} \quad (2a)$$

$$I_{\mathrm{DS0}} = 0, \quad V_{\mathrm{GS}} \le V_{\mathrm{T}} \quad (2b)$$

where all the parameters above are provided in Ref.[12] and can be calculated by using the device physical parameters.

Through comparing expressions (1) and (2a), we assume that I_{1DSS0} is mainly related to $qWN_{\mathrm{D}}^{+}\mu_0$, and the term $\left\{ \dfrac{1}{1+\dfrac{\mu_0 E}{v_{\mathrm{sat}}}} E\left[a-h(x)-h_1(x)\right] \right\}$ in expression (1) is related to $\left(1-\dfrac{V_{\mathrm{GS}}}{V_{\mathrm{T}}}\right)^2 (1+\lambda V_{\mathrm{DS}}) \tanh(\alpha V_{\mathrm{DS}})$. Under this assumption, a new equation combining expressions (1) and (2) is given as

$$I_{\mathrm{DS0}} = A_* qWN_{\mathrm{D}}^{+}\mu_0 \left(1-\frac{V_{\mathrm{GS}}}{V_{\mathrm{T}}}\right)^2 (1+\lambda V_{\mathrm{DS}}) \tanh(\alpha V_{\mathrm{DS}}), \quad (3)$$

where A_* is the ratio coefficient, which is defined as $A_* qWN_{\mathrm{D}}^{+}\mu_0 = I_{\mathrm{DSS0}}$.

Based on expression (3), a CAD oriented drain current model including self-heating effects is developed by modelling the parameters that are presented above and related to temperature and by calculating the junction temperature through the Kirchoff's transformation. In all parameters, the low field electron mobility and ionization rate are the most sensitive parameters associated with temperature caused by self-heating effect.

Based on an empirical low field electron mobility model of 4H-SiC,[13,14] a concise expression to describe the variation of $\mu_0(T)$ with temperature can be shown as follows:

$$\mu_0(T) = \frac{\mu_{300}}{1 + \gamma_0 \dfrac{T}{300} + \gamma_1 \left(\dfrac{T}{300}\right)^2}, \tag{4}$$

where γ_0 and γ_1 are the fitting parameters related to the physics proposed curves of $\mu_0(T) - T$, μ_{300} is the low field electron mobility at 300 K. Expression (4) is more accurate than that from the simple model of low field mobility with $\mu \approx \mu_0 T^{-2.25}$. Figure 2 shows a perfect agreement between simulated results from the present model and the measured data,[13] where μ_{300}, γ_0 and γ_1 are 533 $\mathrm{cm^2/V \cdot s}$, 2.05, and 1.75 respectively, and the doping concentration is $1.6 \times 10^{17}\,\mathrm{cm^{-3}}$.

In order to give a concise and practical expression to describe the in-complete ionization rate, a new model is introduced as follows:

$$N_{\mathrm{D}}^{+}(T) = N_{\mathrm{D}} \times \left[C_{\mathrm{N1}} \left(1 - \frac{300}{T}\right) + C_{\mathrm{N2}} \left(1 - \frac{300}{T}\right)^2 \right], \tag{5}$$

where C_{ND1} and C_{ND2} are fitting parameters, and N_{D} is the total doping density. Figure 3 shows good agreement between simulated results from the present model and from the analytical model,[15–18] where N_{D}, C_{ND1} and C_{ND2} are $1.4 \times 10^{17}\,\mathrm{cm^{-3}}$, –0.080 and –0.094 respectively.

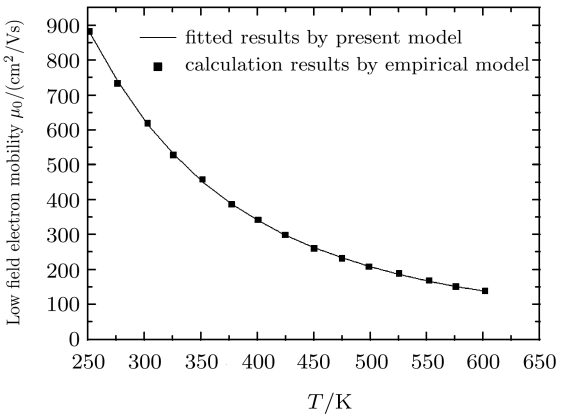


Fig.2. Comparison between simulated results from the present model and from the empirical model[13] for the relation of $\mu_0(T) - T$.

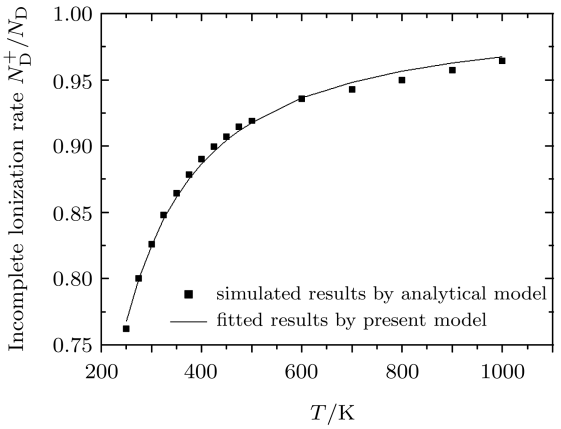


Fig.3. Comparison between simulated results from the analytical model[15–17] and from the present model for the relation of $\dfrac{N_{\mathrm{D}}^{+}}{N_{\mathrm{D}}} - T$.

On the analysis above, a compact and accurate practical drain current expression which accounts for the self-heating effects can be written as

$$I_{\mathrm{DS}} = \frac{C_{\mathrm{ND1}} \left(1 - \dfrac{300}{T}\right) + C_{\mathrm{ND2}} \left(1 - \dfrac{300}{T}\right)^2 / IR_{300}}{1 + \gamma_0 \dfrac{\Delta T}{300} + \gamma_1 \left(\dfrac{\Delta T}{300}\right)^2} I_{\mathrm{DS0}}, \tag{6}$$

where γ_0 and γ_1 can be extracted from the physics proposed curves about $\mu_0(T) - T$, C_{ND1} and C_{ND2} from $N_{\mathrm{D}}^{+}(T) - T$, IR_{300} is in-complete ionization rate of SiC at 300 K, I_{DS0} is the drain current without con-

sidering the self-heating which can be obtained by the pulsed $I-V$ measured. Other parameters in expression (6) are considered as constant when temperature increases, and this assumption is validated (See Section 3).

3. Results, verification and discussion

The SiC MESFET used here refers to that in Ref.[10]. Its cross section is shown in Fig.1. The device consists of a 300 μm thick, high-resistivity 4H-SiC substrate, on which there has been epitaxially grown a 1 μm thick, p-type buffer layer with a net doping level of $5.2\times10^{16}\,\mathrm{cm}^{-3}$, followed by a 0.27 μm thick n-type layer ($1.6\times10^{17}\,\mathrm{cm}^{-3}$) and a 0.2 μm N^+ contact layer ($1.1\times10^{19}\,\mathrm{cm}^{-3}$). The structures have a source/gate spacing of about 0.5 μm and a drain/gate spacing of about 2.5 μm. A channel recess is formed by using a reactive ion etching (RIE) technology. A metallic multilayer (Ti/Pt/Au) is used for the gate, determined by a lift off process, and Au is used to reduce the gate resistance. The source and the drain ohmic contacts are made of nickel, and an SiO_2 passivation layer is used on the top of the device.

Physical parameters involved in the model are listed in Table 2, where the low field mobility is fitted by the calculated results from the empirical model,[13] and the conductivity of 4H-SiC at 300 K is cited from Ref.[16]. The source and the drain parasitic resistances can be obtained by using the method presented in Ref.[19], here they are cited from measured data directly.

Table 1. Device physical and structure parameters.

W	150 μm	K_{00}	3.9W/cm/K
L	1.2 μm	Buffer layer	1μm
t_{sub}	300 μm	a	0.27μm
N_{D}	$1.6\times10^{17}\mathrm{cm}^{-3}$	V_{bi}	0.6
μ_{n0}	533 cm/V·s	V_{T}	–10.5V

Table 2. Extracted parameters about $\mu(T)-T$ and $N_{\mathrm{D}}^{+}(T)-T$.

$\mu(T)-T$	γ_0	γ_1
	2.016	1.11
$N_{\mathrm{D}}^{+}(T)-T$	C_{N1}	C_{N2}
	–0.0965	–0.1005

Table 3. Extracted parameters for I_{DS0} and parasitic resistance.

α_0	0.50 1/V
λ_0	0.0070 1/V
I_{DSS0}	44. 7 mA
$RS+RD$	116
R_i	35

Figure 4 shows a comparison between the simulated results from the present self-heating effect model of expression (6) and the measured data[10] including self-heating effect, and their good agreement is achieved. The junction temperature is calculated from the model in Ref.[20].

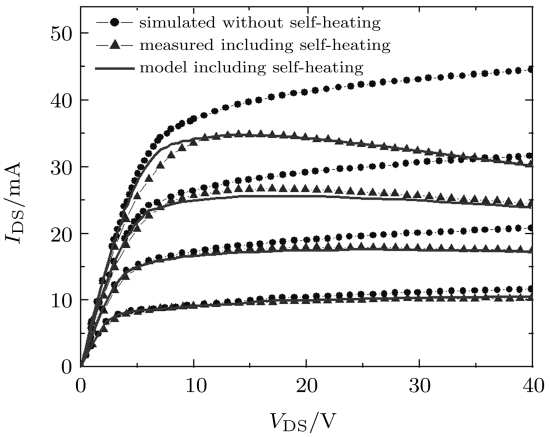


Fig.4. Comparison between the simulated results and the measured data of $I-V$ characteristics of 4H-SiC MESFET with $W=150\,\mu$m and $L=1.2\,\mu$m at $T_{\mathrm{sub}}=300\,$K. $V_{\mathrm{GS}}=-6-0\,$V.

The presented self-heating effect model is based on an analytical drain current model without using the complicated iteration steps. Because it has the concise and practical expressions of parameters, this model can be used in CAD tools easily and thus applied to the designing of 4H-SiC MESFETs-based power circuits. It is also of practical significance that there is no fitting parameter that is directly related to $I-V$ curve, such as α (which is not saturated voltage coefficient here) introduced by Royet and β by Yang. The fitting parameters γ_0 and γ_1 in the presented model here are only dependent on the low field electron mobility; C_{ND1} and C_{ND2} are related to in-complete ionization rate of 4H-SiC, and both are not fitted by drain current directly. This approach should well describe the operational principle for the self heating effect on the device performance.

4. Conclusion

Though the high thermal conductivity of SiC, the self-heating effect for 4H-SiC MESFETs should be also taken into account for the high power RF operation. A CAD oriented and practical useful expression to describe the self-heating effect is derived based on the 4H-SiC MESFET operational principle. The present self-heating model can be used in CAD tools directly and applied to the designing of 4H-SiC MESFET RF power hybrid circuits and MMICs.

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