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Single-Equation Temperature-Dependent DC Model for SiC MOSFET

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Abstract— In recent years, the wide-bandgap Silicon-Carbide (SiC) MOSFET is proposed as a solution to considerably reduce power losses in power transistor switches. This paper presents an improved single-equation temperature-dependent DC model for SiC MOSFET. Using one equation, the proposed model avoids the problems of continuities at the high order derivatives of the drain current at the transition regions encountered in the piece-wise transistor models. In addition, all peculiar features observed in the experimental *I-V* characteristics of the SiC MOSFET are perfectly reproduced by the model, namely: i) the moderate inversion region, or region of low drain current observed at low gate voltage, ii) the gradual increase of drain current from linear to saturation region and pinch-off region noticed in the output characteristics and iii) the quasi-saturation effect, which appears at high gate voltage by a less sensitivity of the drain current to the rise in gate voltage compared to classical saturation. The advantage of the proposed model - over the existing single-equation SiC models - is the independence of its parameters against bias voltages, manufacturer process and technology. Simple and efficient parameter extraction method is provided using an optimizer algorithm with good initial parameter values. The model's scalability with temperature is ensured through its temperature-dependent parameters. Validity of the proposed model is executed through its comparison with CoolSiC trench MOSFET, TCAD simulation and measurement. Excellent agreement is acheived, confirming that the proposed model can be implemented in circuit simulators to represent the SiC MOSFET devices.

Keywords— SiC power MOSFET; SPICE model; Parameter extraction; TCAD simulation.

1. INTRODUCTION

In power electronic applications, the unipolar power MOSFET (see Fig. 1) is widely used as a switch to control the flow of electric energy. The Silicon (Si)-based power MOSFET is employed in several power electronic applications thanks to its high switching frequency, high input impedance and thermal stability [1]. However, the Si power MOSFET suffers from the breakdown voltage/on-resistance (V_{BR}/R_{on}) compromise, so a high-voltage Si power MOSFET will have very high on-resistance. Therefore, the Si power MOSFET was limited to low voltage power applications. Thanks to advances in technology, the SiC MOSFET is commercially available having better V_{BR}/R_{on} compromise compared to its Si counterpart. In fact, the high critical breakdown field of SiC leads to smaller device size of the SiC MOSFET compared to the Si power MOSFET with similar breakdown voltage [2, 3]. Consequently, the on-resistance and the inter-electrode capacitances of the SiC MOSFET are considerably reduced, leading to lower losses. Furthermore, SiC MOSFET can operate at high temperature because of the high thermal conductivity of SiC which is 3 times higher than that of Si [3, 4].

In recent published literature, several models for SiC MOSFET have been introduced in order to integrate this device in circuit simulators [5-17]. These models are divided into two

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categories: 1) the piece-wise models which use different formulations of the drain current at different operating regions of the device [5-13] and 2) the single-equation models which use one equation of the drain current at all the operating regions of the device [14-17]. The piece-wise models are generally avoided because of the discontinuity constraint of the first or higher-order derivatives at the boundaries between the drain current formulations. In other way, the single-equation model can be a solution to handle the problem of the first and higher-order derivative discontinuities. In [14], the authors use single-equation model for SiC MOSFET based on sub-circuit composed of a standard MOSFET, representing the channel region, in series with bias dependent resistance that represents JFET and accumulation regions, and constant drift resistance. This model uses floating nodes, and its drain current is defined by using complex subcircuit based on gate-voltage dependent current source. Model [15] is an extension of the EKV model using single-equation to reproduce the static *I-V* characteristics of the SiC MOSFET. Nevertheless, this model uses some parameters which are fixed by means of unphysical fitting coefficients. Models [16] and [17] propose a single-equation model for SiC MOSFET based on Curtice model [18] and the Angelov model [19] respectively. While these two models give accurate simulations, they use gate-voltage dependent parameters to fit the static *I-V* characteristics of SiC MOSFET. As a result, these bias dependent parameters increase the complexity and simulation time of the model.

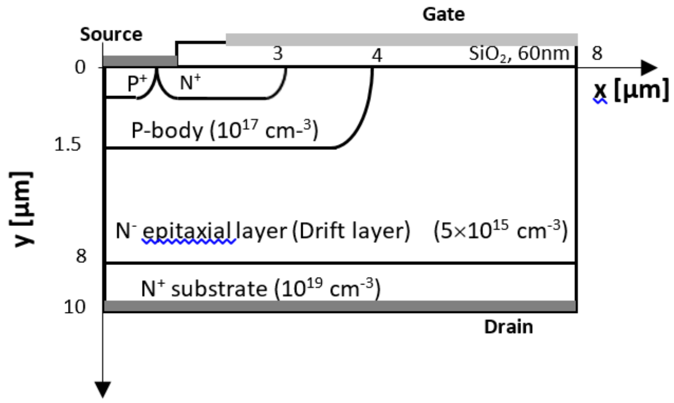

Fig. 1. Half-cell structure of the SiC MOSFET used in TCAD simulations.

The objective of the present work is to propose a single-equation temperature-dependent static model for the SiC MOSFET, avoiding discontinuity problems without any dependence on bias voltages, manufacturing process and technology. The model is an extended version of the Curtice model which was introduced to model the GaAs MESFET transistor [18]. Modifications are made to build a compact model that can simulate, with high-precision, the static electric behavior of the SiC MOSFET in all its operating regions over a wide temperature range. All peculiar features observed in the dc *I-V* characteristics of SiC MOSFET will be taking into account by the model: 1) the moderate inversion region, 2) the gradual increase of drain current in pinch-off region noticed in output characteristics and 3) the quasi-saturation effect [20]. Temperature dependence of the model is performed by the temperature scaling parameters. All model parameters are extracted from the experimental *I-V* device characteristics by using simple and efficient optimizer program [21]. The model is validated versus datasheet data, TCAD simulation and measurement.

This paper contains the following sections. Section 2 shows the proposed model formulation and gives the definition of each model parameters. Section 3 involves the parameter extraction procedure. Section 4 presents results and discussion of the comparison between model, datasheet data, TCAD simulation and measurement. Finally, a conclusion which completes the proposed article is given in section 5.

2. MODEL DESCRIPTION

In this section, we explain the modeling approach with giving details of the model parameter origin. Our proposed temperature-dependent static model is an extension of the Curtice model [18] to the SiC MOSFET. In the Curtice model, the formalism of the drain current uses tangent hyperbolic mathematical function which provides smooth transition between linear and saturation region in output characteristics. The Curtice model uses the following equation to describe the drain current in GaAs MESFET

$$I_{DS} = \beta\left(V_{GS} + V_T\right)^2\left(1 + \lambda V_{DS}\right)\tanh\left(\alpha V_{DS}\right) \tag{1}$$

Where V_{GS} is the gate-source voltage and V_{DS} is the drain source voltage. β is the transconductance parameter. V_T is the pinch-off voltage parameter, and λ is the channel length modulation parameter. α is a scaling parameter which has an effect on the curvature of the *I-V* output characteristics. While this model is accurate for GaAs MESFET, it cannot model the SiC MOSFET because of its special *I-V* characteristics. These peculiar characteristics of the SiC MOSFET are due to the SiC semiconductor material properties and the device-physical structure (see Fig. 1).

In [16], authors propose an extended version model based on the Curtice model for both GaN HEMT and SiC MOSFET devices. However, this model uses fitting terms based on bias voltage-dependent parameters to reproduce the transition regions in output and transfer characteristics. Consequently, the complexity and the simulation time of the model will increase.

In this paper, we propose to introduce practical modifications to Curtice model in order to obtain a smooth static model for SiC MOSFET with parameters independently of bias voltages, manufacturing process and technology. In order to reproduce accurately the *I-V* characteristics of the device at different temperatures, we have also incorporated model parameters whose values depend on temperature. For this purpose, our model proposes the following formalism of the drain current:

$$I_{DS} = I_{DSAT}\left(1 + \lambda V_{DS}\right)\tanh\left(\frac{V_{DS}}{f\left(V_{GS}\right)}\right) \tag{2}$$

I_{DSAT} is the saturation drain current at high V_{DS}. f(V_{GS}) is the saturation drain voltage function which defines the I_{DS}-V_{DS} curvature in output characteristics versus V_{GS}. The final proposed formalism of the drain current is given by:

$$I_{DS} = \frac{B\left(V_{GS} - V_T\right)^n}{1 + \theta\left(V_{GS} - V_T\right)^\gamma}\left(1 + \lambda V_{DS}\right)\tanh\left(\frac{V_{DS}}{K\left(V_{GS} - V_T\right)^m}\right) \tag{3}$$

Parameters K and m define the saturation drain voltage function; they allow to model perfectly the gradual transition between linear and saturation region observed in output characteristics of the SiC MOSFET. B and n parameters adjust the saturation drain current value and the slope of the I_{DS}-V_{DS} output characteristics in linear region. V_T is the threshold voltage parameter, θ an γ control the reduction of drain current at high gate voltage due to the transverse electric field. The exponent parameter γ is added to give the model additional degree of freedom to reproduce more precisely the quasi-saturation region [20].

For low V_{DS}, the approximate drain current can be written as:

$$I_{DS} = \frac{B\left(V_{GS}-V_T\right)^{n-m}}{K\left(1+\theta\left(V_{GS}-V_T\right)^{\gamma}\right)}V_{DS} \tag{4}$$

This equation is equivalent to the linear equation of the nth-power law MOSFET model at low V_{DS} [22] by adding the term corresponding to effect of the transverse electric field (1+θ(V_{GS}-V_T)$^{\gamma}$). The n^{th}-power law MOSFET model was introduced to model properly the short channel MOSFETs [22].

For high V_{DS}, the approximate drain current equation can be given by:

$$I_{DS} = \frac{B\left(V_{GS}-V_T\right)^{n}}{1+\theta\left(V_{GS}-V_T\right)^{\gamma}}\left(1+\lambda V_{DS}\right) \tag{5}$$

This approximate saturation drain current is similar to the saturation drain current in the n^{th}-power law MOSFET model [22] by adding the transverse electric field effect. From Eqs. (4) and (5), we can see clearly the importance of term ((1+θ(V_{GS}-V_T)$^{\gamma}$), related to transverse electric field, which will allow to reduce the drain current at high gate voltage.

The static characteristics of the SiC MOSFET are influenced by variation in temperature. In order to predict accurately the static electrical behavior of the SiC MOSFET under various temperatures, the proposed model have the following temperature dependent parameters: K, B, θ and V_T. In this modeling, we choose to express these temperature scaling parameters as follows [8]:

$$K_T = K_0\left(\frac{T}{TNOM}\right)^{EXPKT} \tag{6}$$

$$B_T = B_0\left(\frac{T}{TNOM}\right)^{EXPBT} \tag{7}$$

$$\theta_T = \theta_0\left(\frac{T}{TNOM}\right)^{EXP\theta T} \tag{8}$$

$$VTT = VT - TCVT\left(T - TNOM\right) \tag{9}$$

T is the temperature scaled, and $TNOM$ is the nominal temperature (298 K). K_0, B_0, θ_0 and V_T are the values of parameters at T=$TNOM$. $EXPKT$ is K parameter temperature coefficient, $EXPBT$ is B parameter temperature coefficient, and $EXP\theta T$ is θ parameter temperature coefficient. $TCVT$ is a threshold-voltage temperature coefficient.

3. PARAMETER EXTRACTION PROCEDURE

In order to obtain proper model parameters, we use the parameter extraction procedure provided in [21] which uses nonlinear least square optimization program. The starting point initial values of the model parameters are extracted by using the traditional extraction method based on current approximation in different operating regions of the device [21].

In the present work, we choose to fix the starting initial values of m, n, θ, γ, and λ parameters as follows: m = 1, n = 2, θ = 0, γ = 1 and λ = 0. In this starting condition, we neglect the effect of the transverse electric field and the channel length modulation. Therefore, the saturation drain current equation is reduced to I_{DSAT} = B(V_{GS}-V_T)^2. The latter is similar to the saturation drain current in Shichman-Hodges MOSFET model. The starting point initial value of the saturation scaling parameter B is extracted from the slope factor in the transfer characteristic at high V_{DS} (Fig. 2). The starting point initial value of the threshold voltage parameter V_T is extracted from the slope of drain current in transfer characteristic at low gate voltage (see Fig. 2).

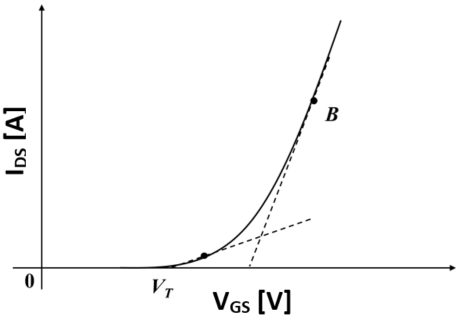

Fig. 2. Extraction procedure for starting point initial values of B and V_T parameters.

The starting initial value of the scaling parameter K, related to output characteristics, is extracted in linear region of the output characteristics at low V_{DS}. The initial value of K is determined from Eq. (4) at a selected point in linear region of output characteristics.

The initial guess values of the temperature scaling coefficients ($EXPKT$, $EXPBT$, $EXP\theta T$, $TCVT$) are obtained from Eqs. (6) to (9) at two temperatures. In this work, the nominal temperature $TNOM$ is set to 298 K.

4. RESULTS AND DISCUSSION

To validate the proposed study, the model was introduced in PSPICE simulator to perform the simulations. The model netlist is given in Fig. 3.

```
PSPICE Temperature-dependent DC Model for SiC MOSFET
.SUBCKT SiCMOSFET G D S
******* Parameter declarations
.Param B0= K0= VT= LAMBDA=
.Param THETA0= m= n= GAMMA=
.Param EXPK= EXPB= TCVT= EXPTH=
.Param TNOM=
.Param T={Temp+273}
.Param KT={K0*(T/TNOM)^EXPK}
.Param BT={B0*(T/TNOM)^EXPB}
.Param THETAT={THETA0*(T/TNOM)^EXPTH}
.Param VTT={VT-(TCVT*(T-TNOM))}
******* Saturation Drain current IDSAT
.FUNC IDSAT(Vds,Vgs) {BT*((Vgs-VTT)^n)*(1+LAMBDA*Vds)/(1+THETAT*(Vgs-VTT)^GAMMA)}
******* Drain-source saturation voltage function VDSAT(Vgs)
.FUNC VDSAT(Vgs) {KT*((Vgs-VTT)^m)}
********** Drain current function
.FUNC IDS(Vds,Vgs) {IF(Vgs<=VTT,0,IDSAT(Vds,Vgs)*tanh(Vds/VDSAT(Vgs)))}
GMOS D S value {Ids(V(d,s),V(g,s))}
.ends SiCMOSFET
```

Fig. 3. PSPICE netlist of the proposed dc SiC model.

PSPICE simulation results will be compared to CoolSiC MOSFET datasheet, DMOSFET TCAD simulation and measurement. TCAD simulations are obtained by using the half-cell structure of 1.2 kV, 4 mΩ·cm² 2D SiC DMOSFET (see Fig. 1) [23].

Figs. 4 and 5 show the comparison between static *I-V* characteristics of the model and the datasheet of the CoolSiC 1200V SiC trench MOSFET IMZ120R140M1H provided in [24] at *Tj* = 25 °C and *Tj* = 175 °C. Excellent agreement is obtained by the proposed model with mean percentage error (MPE) less than 6%.

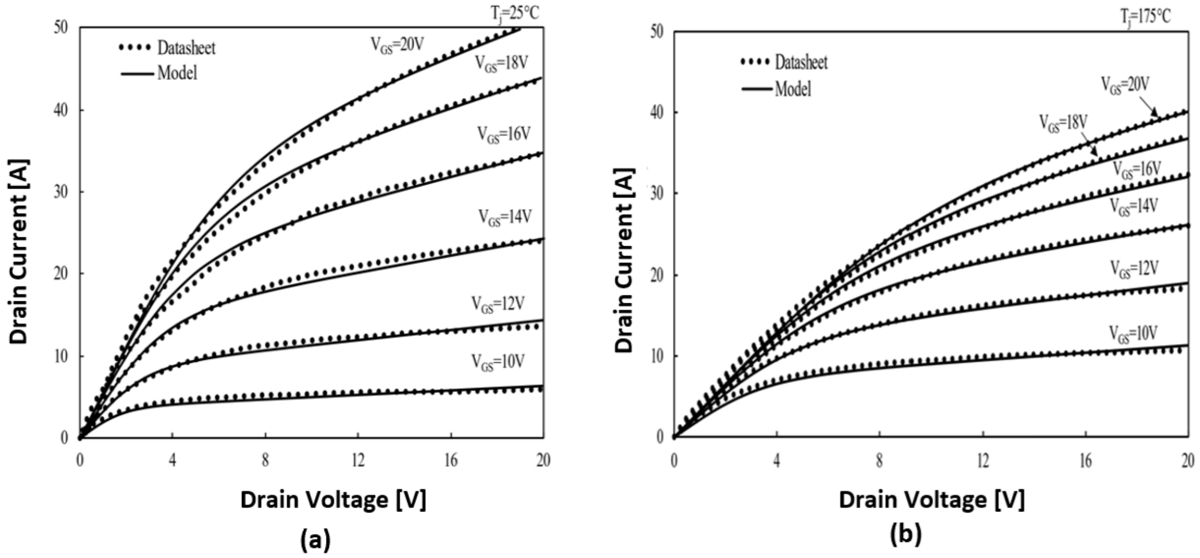

Fig. 4. Output characteristics of the proposed model and CoolSiC MOSFET IMZ120R140M1H from [24] at: a) 25 °C; b) 175 °C.

As shown in Figs. 4 and 5, the model reproduces correctly the entire static characteristics of the CoolSiC MOSFET considering: 1) the gradual increase of drain current in the pinch-off region noticed in the output characteristics and 2) the crowding of curves, due to the quasi-saturation effect, in output characteristics at high gate voltages which is also visible by the reduction in drain current in transfer characteristic.

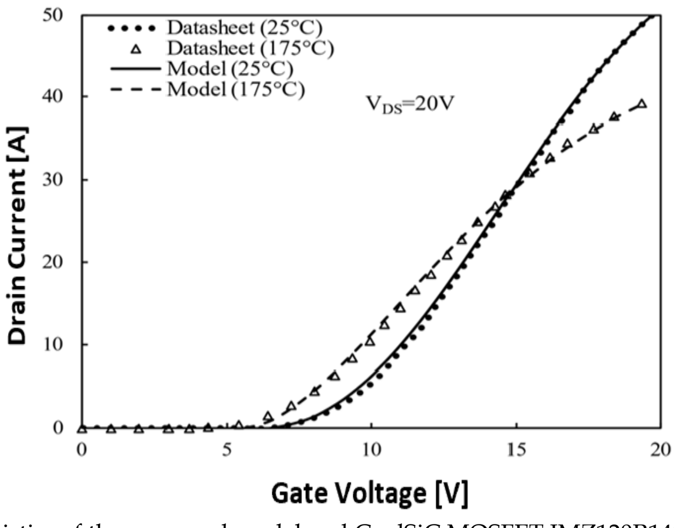

Fig. 5. Transfer characteristics of the proposed model and CoolSiC MOSFET IMZ120R140M1H from [24] at 25 °C and 175 °C.

Fig. 6 compares the model versus TCAD simulation at 25 °C, 75 °C and 150 °C. Table 1 gives the model parameter values extracted from TCAD simulation. Good simulation results are obtained with MPE less than 5%, a fact which validate the temperature-scalability of the model.

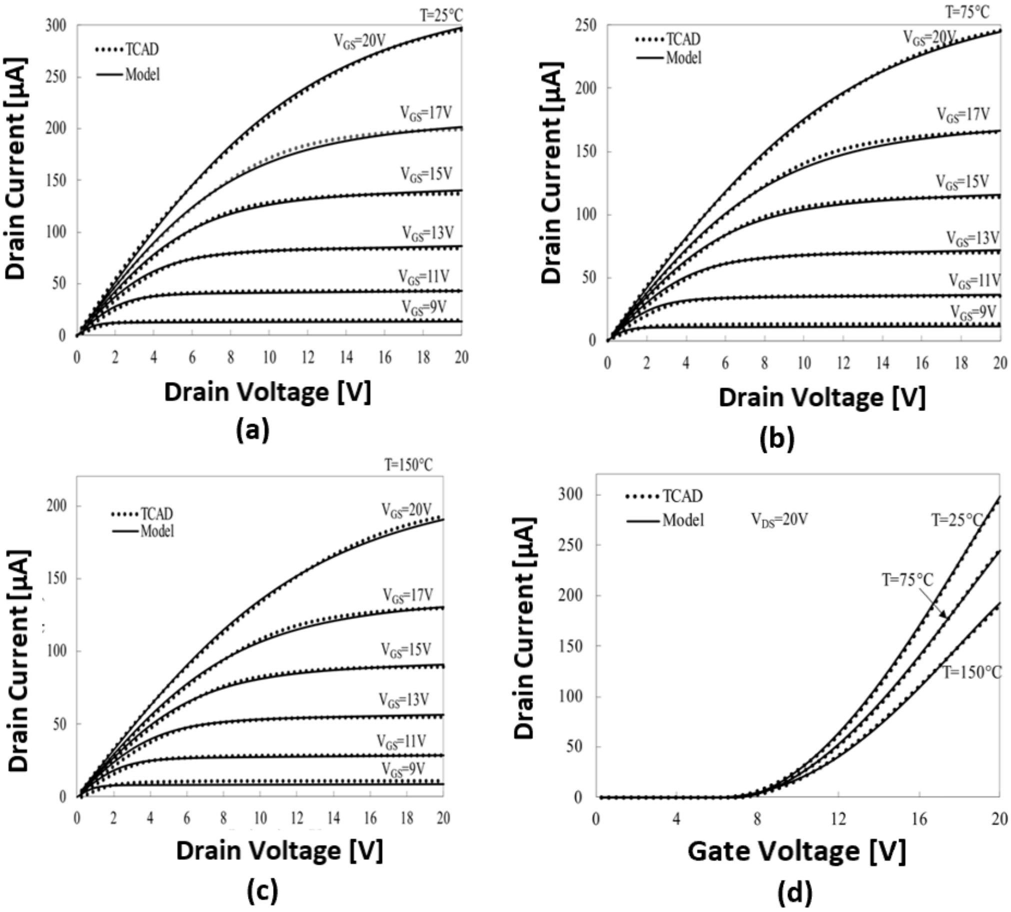

Fig. 6. Output characteristics of model and TCAD simulation at: a) 25 °C; b) 75°C; c) 150 °C and d) transfer characteristics.

Table 1. Extracted parameter values for the simulated 2D TCAD.

Par. symbol	Parameter	Value	Unit
V_T	Threshold voltage (at *TNOM*)	6.97	V
B_0	Scaling drain current saturation parameter (at *TNOM*)	3.71×10^{-7}	A/V^n
K_0	Parameter related to transition region in output characteristics (at *TNOM*)	0.346	V^{1-m}
θ_0	Transverse electric field coefficient (at *TNOM*)	3.62×10^{-3}	$V^{-\gamma}$
λ	Channel length modulation parameter	4.49×10^{-3}	V^{-1}
m	Parameter related to saturation voltage function	1.35	-
n	Parameter related to I_{DSAT}	1.72	-
γ	Parameter related to the transverse electric field and quasi-saturation region	1.12	-
EXPBT	*B* temperature coefficient	-1.22	-
EXPKT	*K* temperature coefficient	0.144	-
EXPTθT	θ Temperature coefficient	0.479	-
TCVT	V_T temperature coefficient	-5.63×10^{-8}	V/K

Fig. 7 shows comparison between model and experimental data provided by [25]. The proposed single-equation model fits properly the static output and the transfer characteristics at low and high drain voltages with MPE less than 9%. Finally, comparison on model complexity and simulation speed between the proposed model and models [16] and [17] is giving in Table 2.

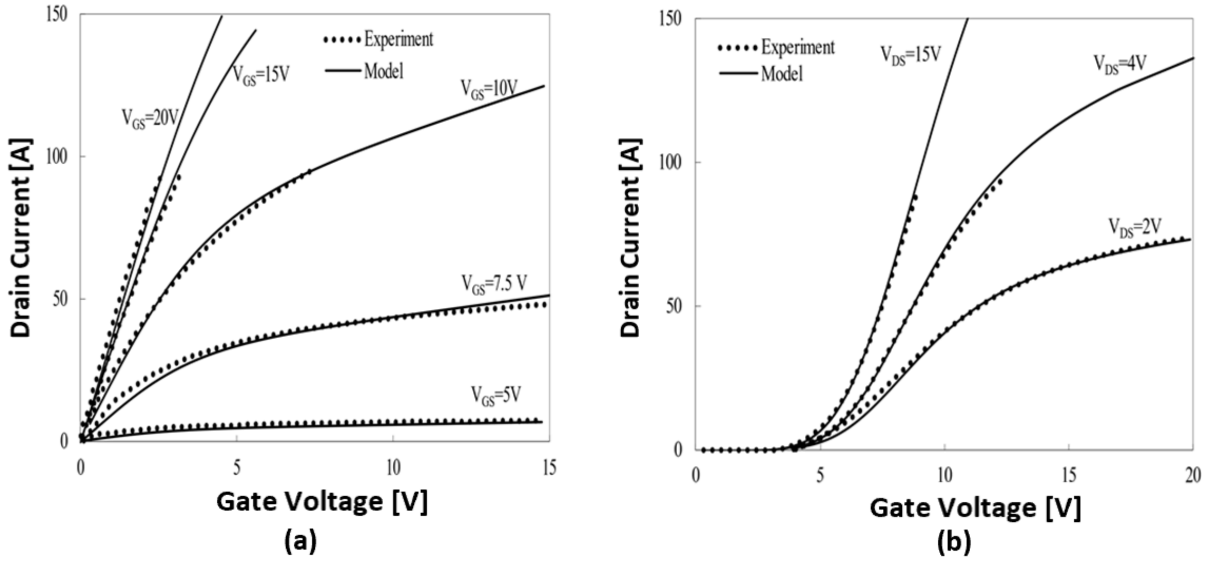

Fig. 7. Static I-V characteristics of model and experimental data obtained from [25]: a) output characteristics; b) transfer characteristics.

Table 2. Comparison between the proposed model and the models reported in [16, 17].

Parameter		Proposed model	Model [16]	Model [17]
Model complexity	Type	7 fixed parameters	5 fixed parametres and 2 gate voltage depended parametres	5 gate voltage depended paramatres
	extraction method	- Simple & detailed - Optimazation method based on Levenberg-Marquardt algorithm [21] - Initial guess of unkown parameter based on Shichman-Hodges model	- Optimization algorithm not specified - The choice of initial guess not specified	- Optimization algorithm not specified - The choice of initial guess not specified
Simulation speed		0.19 ms	0.34 ms	0.34 ms

5. CONCLUSIONS

In this paper, an accurate temperature-dependent dc model for SiC MOSFET is presented. This model - which is an extended version of the Curtice model - uses a single-equation with independent parameters of bias voltages, manufacturing process and technology. Compared to reported in literature single-equation models, the proposed model is simple, continuous and uses few parameters. The model parameters are extracted using an optimizer program based on good initial condition. All operating regions of the SiC MOSFET are reproduced perfectly by the model at different temperatures. Moreover, the proper formulation of drain current versus bias voltages allows the model to take into account the quasi-saturation regime and all transition operating regions of the device. The simple formalism of the model allows easier implementation of its netlist in circuit simulation with improving simulation speed and convergence.

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