An Optimal Parameter Extraction Procedure for SiC Power MOSFET Model

Hicham Er-rafii and Abdelghafour Galadi

National School of Applied Sciences, Cadi Ayyad University, Safi, Morocco
e-mail: Hicham.Er-rafii@ced.uca.ma

***Abstract*—A simple and efficient parameter extraction method for Silicon Carbide (SiC) power MOSFET model is described. This method uses nonlinear optimization algorithm to find the optimal set of parameters to model. The optimizer algorithm starts with initial guess parameters, extracted from measurement, to provide a set of parameters minimizing errors between model and measurements data in entire operating regions of the device (Average percent error less than 10 %). The starting initial guess parameter values give to the algorithm a closed solution to obtain the optimal set of model parameters with reduced iteratives. The efficiency of the proposed extraction method is proved with the good agreements obtained between the model and the measurements.**

***Index Terms*—Device modeling, Optimization procedure, Parameter extraction, SiC MOSFET, SPICE simulation.**

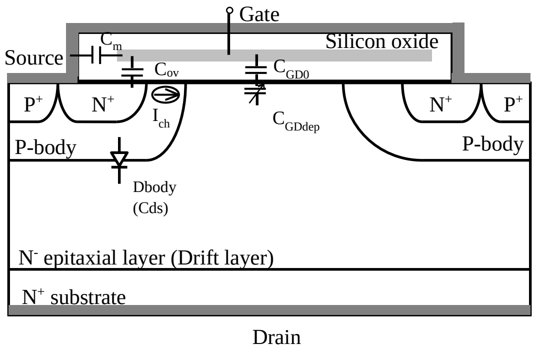

Fig 1. Conventional power MOSFET structure with its internal model elements

I. Introduction

The unipolar power MOSFET transistor is widely used in the power electronic applications thanks to its high input impedance, high switching speed and thermal stability. The majority-carrier power MOSFET device integrates in its structure the high voltage drift region (Fig. 1). Breakdown voltage of the power MOSFET is determined by the thickness and the doping level of the drift epitaxial layer [1]. Unlike the bipolar power devices, which benefit from the drift layer conductivity modulation to reduce the on-resistance, the unipolar Silicon (Si) power MOSFET device is limited to medium voltage applications because of its high on-resistance. In recent years, SiC power MOSFET devices with very low on-resistance were proposed by the most power semiconductor manufacturers [2]−[4]. SiC power MOSFET devices present low on-resistance and low parasitic capacitances thanks to the higher breakdown electric field of SiC compared to Si [4]. In SiC power MOSFET device the drift layer is thinner and highly doped compared to the drift layer in Si power MOSFET device with the same breakdown voltage.

In literature, various models for SiC power MOSFET were proposed [5]−[13]. These models use a subcircuit consisting of an equivalent circuit based on device physic. The subcircuit combines a traditional MOSFET transistor, representing the channel region, with resistances, capacitors, inductances and dependent/independent current/voltage sources to model the electrical behavior of the power MOSFET. Two methods are used to extract parameters of the SiC power MOSFET models: the traditional parameter extraction method and the nonlinear least square optimization method. In the traditional extraction method [5]−[11], the parameter values are determined in selected operating regions of the I-V and C-V curve measurements. Therefore, this method can introduce disagreements between model and experimental data in the operating regions of device [14]. In the nonlinear least square optimization method [12], [13], the parameter values are extracted by using algorithm to find the minimum errors between model and experimental data in the entire operating regions of the device. Therefore, this method can produce accurate parameters if good initial guess and proper model equation are provided to the optimization program. The parameter extraction method proposed in [12] uses simplified model based on [11] with help of Levenberg-Marquardt (LM) algorithm. In this model the drain current uses simplified equation which cannot describe correctly the drain current in all operating regions of the SiC power MOSFET devices. In addition, LM algorithm used in [12] needs accurate initial guess values of parameters to provide convergence to optimal solution. In [13], authors propose a SiC power MOSFET model based on model parameters extracted by using two algorithms: genetic algorithm GA combined with LM algorithm. GA is used to give the initial guess to LM algorithm then LM is used to determine the model parameters [13]. In [15], authors present a method of parameter extraction based on stochastic optimization, but the initial values of some parameters are not justified. Article [16] presents a method that improves the execution time of the optimization process based on the automatic derivative (AD), This new method is not available in such as optimization solver; it requires to be programmed.

In this paper, an improved parameter extraction procedure for SiC power MOSFET models is presented. The proposed extraction method combines the traditional extraction method and the nonlinear least square optimization method. First, the initial guess values of the parameters will be

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extracted empirically by using the traditional extraction method. Next, these initial guesses of parameters will be introduced as starting point in the nonlinear least square optimization algorithm. This method can help the optimization algorithm to converge to optimal solution in few iterations. In the present work, LM algorithm will be used to find the optimal model parameters. The LM algorithm is a widely used method to solve nonlinear least squares problems [12], [13]. Finally, it will be shown that optimization program requires proper I-V model equations with good initial guesses to provide optimal set of parameters to the model.

For this purpose, section 2 describes the chosen static and dynamic model equations. Section 3 is devoted to the procedure of parameter extraction and section 4 shows the model simulation results compared to datasheet and experimental data.

II. MODEL EQUATIONS

The model uses current source I_{DS} to describe the drain current versus gate-source and drain-source voltages. The drain current equations are based on [11] with introducing channel-length modulation parameter λ in linear and saturation regions to avoid discontinuity problem in the model at the pinch-off voltage. In this paper, we choose to use the static model published in [11] thanks to its simplicity and its proper model equations to describe the static *I-V* curves of SiC power MOSFET devices. In accordance with the transfer characteristic, it is seen that the threshold voltage and the slope of the transconductance parameter vary with gate voltage regions: high and low current regions. The drain current is the sum of two current components: low drain current and high drain current relating to the gate voltage regions [11]. Firstly, the drain current is defined in [11] by:

$$I_{DS} = I_{DSL} + I_{DSH} \qquad (1)$$

In linear region, the drain current is defined as follows:

$$I_{DSL} = \frac{K_{fl} K_f K_p \left[(V_{GS} - V_{TL}) V_{DS} - \frac{P_{VF}{}^{y-1} V_{DS}{}^{y} (V_{GS} - V_{TL})^{2-y}}{y} \right]}{\left(1 + \theta (V_{GS} - V_{TL})\right)} (1 + \lambda V_{DS}) \quad for \quad V_{DS} \le \frac{V_{GS} - V_{TL}}{P_{vf}}$$

$$I_{DSH} = \frac{(1 - K_{fl}) K_f K_p \left[(V_{GS} - V_{TH}) V_{DS} - \frac{P_{VF}{}^{y-1} V_{DS}{}^{y} (V_{GS} - V_{TH})^{2-y}}{y} \right]}{\left(1 + \theta (V_{GS} - V_{TH})\right)} (1 + \lambda V_{DS}) \quad for \quad V_{DS} \le \frac{V_{GS} - V_{TH}}{P_{vf}} \qquad (2)$$

In saturation region, the drain current is defined as follows:

$$I_{DSL} = \frac{K_{fl} K_p (V_{GS} - V_{TL})^2}{2\left(1 + \theta (V_{GS} - V_{TL})\right)} (1 + \lambda V_{DS}) \quad for \quad V_{DS} > \frac{V_{GS} - V_{TL}}{P_{vf}}$$

$$I_{DSH} = \frac{(1 - K_{fl}) K_p (V_{GS} - V_{TH})^2}{2\left(1 + \theta (V_{GS} - V_{TH})\right)} (1 + \lambda V_{DS}) \quad for \quad V_{DS} > \frac{V_{GS} - V_{TH}}{P_{vf}} \qquad (3)$$

where V_{GS} is the gate-source voltage and V_{DS} is the drain-source voltage. K_p is the saturation region transconductance parameter while K_f is the linear region transconductance factor. The parameter λ is added to take into consideration the channel length modulation. The reduction in channel mobility due to the high transverse electric field at high gate voltages is taking into account through the model parameter θ. V_{TH} is the threshold voltage relating to high current region. V_{TL} is the threshold voltage relating to low current region. V_{TH} and V_{TL} are introduced in the model expressions by using the threshold voltage parameter V_T, the low current threshold voltage parameter dV_{TL} and the low current transconductance coefficient K_{fl}.

$$\begin{cases} V_{TL} = V_T - dV_{TL} \\ V_{TH} = V_T + \dfrac{K_{fl}}{1 - K_{fl}} dV_{TL} \end{cases} \qquad (4)$$

The pinch-off voltage factor P_{vf} is introduced in model to consider the gradual transition of the drain current between linear and saturation regions noticed in SiC power MOSFET devices. y is a pinch-off voltage exponent which ensures that the drain current equation and its first derivative are continuous at pinch-off voltage:

$$y = \frac{K_f}{K_f - \frac{P_{vf}}{2}} \qquad (5)$$

The transient behavior of power MOSFET is determined by the oxide and depletion capacitances of the device (Fig. 1). The parasitic interelectrode capacitances of the power MOSFET structure are divided into three capacitances: gate-source capacitance C_{GS}, gate-drain capacitance C_{GD} and drain-source capacitance C_{DS}. C_{GS} is a constant capacitance and it's the sum of two capacitances in parallel: the capacitance between gate and source metallization C_m and the overlap capacitance between the gate metallization and the N^+ diffusion source C_{ov} (Fig. 1). Therefore, C_{GS} is modeled by using single constant capacitance C_{GS} parameter.

The gate-drain capacitance C_{GD} is a series equivalent capacitance of the gate oxide capacitance C_{GD0} and depletion layer capacitance C_{GDdep} (Fig. 1). In this work, we choose to represent C_{GD} by the following empirical equation proposed in [17]

$$C_{GD} = \begin{cases} A \tanh(a V_{GD}) + B & if \quad V_{GD} > 0 \\ C \operatorname{atan}(a V_{GD}) + D & if \quad V_{GD} \le 0 \end{cases} \qquad (6)$$

where *A*, *B*, *C* and *D* parameters depend on the minimum value of C_{GD} (C_{GDmin}) and the maximum value of C_{GD} (C_{GDmax}). The parameter *a* is used to fit the slope of measured C_{GD}-*V* curve to model.

The drain-source capacitance C_{DS} is a junction depletion capacitance depending in drain-source voltage V_{DS}. C_{DS} is determined by the depletion width of drain-source junction. The equation used to model C_{DS} is given by

$$C_{DS} = \frac{C_{DS0}}{\left[1+\frac{V_{DS}}{V_{JD}}\right]^{MD}} \quad (7)$$

C_{DS0} is the zero drain-source bias capacitance, MD is the drain-source grading coefficient and V_{JD} is the drain-source junction potential.

III. PARAMETER EXTRACTION PROCEDURE

The model parameter extraction is a very important step to obtain model that can accurately reproduce the measured *I-V* and *C-V* characteristics of the device. The right parameters lead to very good simulation results compared to the measured data. In this work, the unknown model parameters will be extracted by using nonlinear least square optimizer to obtain optimal parameters for the SiC power MOSFET model. The optimizer will give the optimal set of parameters by matching the measured data points to the model in entire operating regions of the device. In order to reduce the number of iterations and help algorithm to converge to the optimal solution, the initial guess values of unknown model parameters will be extracted by using the traditional extraction method based on measured *I-V* and *C-V* device characteristics.

A. Parameter optimization algorithm

The optimization algorithm determines the model parameters by reducing the sum of the squared errors between measured data points (I_i) and the model ($I(x,V_{GSi},V_{DSi})$) formulated with the error function (8). In (8), V_{GSi} and V_{DSi} are known parameters extracted from measurements while θ, VT, $dVTL$, Kfl, Kp, Kf, Pvf and λ are the unknown static parameters represented by x. In the same way, the dynamic model parameters will be determined using the algorithm with replacing I_i by the measured capacitances C_i and $I(x,V_{GSi},V_{DSi})$ by the model of capacitances $C(z,V_{GSi},V_{DSi})$ in (8). C_{GS}, a, A, B, C, D, C_{DS0}, V_{JD} and MD are the unknown dynamic parameters represented by z. Fig. 2 shows the implementation of LM algorithm with introducing the extracted model parameters as initial guesses values. The model is described by (1) to (7). The starting point of the LM algorithm is fixed by using the traditional extraction method. Then, LM algorithm research the fitting parameters reducing the sum of squared errors between model and measured data points by iterative approach. For the static parameters, the error function is defined by

$$ERRF = \sum_{i=1}^{m}\left(I_i - I\left(x, V_{GSi}, V_{DSi}\right)\right)^2 \quad (8)$$

m is the number of measured data points. I_i is the measured drain current at $V_{GS} = V_{GSi}$ and $V_{DS} = V_{DSi}$. $I(x, V_{GSi}, V_{DSi})$ is the drain current obtained by the model and x is a vector of the unknown parameters. The initial guess values of the unknown parameters are introduced in computer program to provide convergence, avoid unphysical parameter solution and reduce the number of iterations.

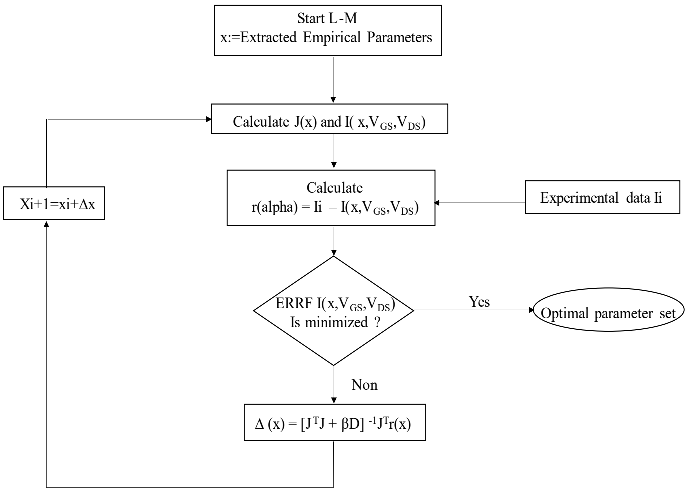


Fig 2. Flowchart of parameter extraction method using LM algorithm

```
#The python script used for the parameters extraction (static part)
import numpy as np
from scipy.optimize import least_squares
import xlwings as xw    #this library is used to import data (measured voltage, measured current) from Excel
ws = xw.Book("workbook name.xlsx").sheets['sheet name']; #the workbook must be open
VDS=ws.range("specify the range of the VDS voltage").value;  #for example: VDS=ws.range("C4:C200").value
VGS=ws.range("specify the range of the VGS voltage").value;
IDS_measured=ws.range("specify the range of the measured IDS current").value;
def       ERRF(x,VGS,VDS,IDS_measured): #x:the vector of parameters
  Kf=x[0]; Kp=x[1]; Pvf=x[2]; Theta=x[3]; Lambda=x[4]; dVT=x[5]; VT=x[6]; Kfl=x[7];
  y=Kf/(Kf-Pvf/2);
  VTh=VT+Kfl*dVT/(1-Kfl);
  VTl=VT-dVT;
  m= "number of measurements" ;
  IDS_model=np.empty(m);
  for i in range(m):
    Vds=VDS[i]; Vgs=VGS[i];
    Vdsatl=(Vgs-VTl)/Pvf;
    Vdsath=(Vgs-VTh)/Pvf;
    if Vgs<VTl:
      Imosl=0;
    else:
      if Vds<Vdsatl:
        Imosl=(Kfl*Kf*Kp)*((Vgs-VTl)*Vds-((Pvf**(y-1))*Vds**(y)*((Vgs-VTl)**(2-y)))/y)/(1+Theta*(Vgs-VTl));
      else:
        Imosl=Kfl*Kp*((Vgs-VTl)**2)/(2*(1+Theta*(Vgs-VTl)));
    if Vgs<VTh:
      Imosh=0;
    else:
      if Vds<Vdsath:
        Imosh=((1-Kfl)*Kf*Kp)*((Vgs-VTh)*Vds-((Pvf**(y-1))*Vds**(y)*((Vgs-VTh)**(2-y)))/y)/(1+Theta*(Vgs-VTh));
      else:
        Imosh=(1-Kfl)*Kp*((Vgs-VTh)**2)/(2*(1+Theta*(Vgs-VTh)));
 IDS_model[i]=(Imosl+Imosh)*(1+Lambda*Vds);
  return IDS_model-IDS_measured
x0=[];  #x0: the initial guess of the L-M algorithm (x0=[Kf0,Kp0,Pvf0,Theta0,Lambda0,dVT0,VT0,Kfl0])
sol = least_squares(ERRF,x0,method='lm',ftol=1e-9,xtol=1e-9, max_nfev=int(1e6),args=(VGS,VDS, IDS_measured))
print(sol)
```

Fig 3. The python script of the proposed extraction method using the LM algorithm

The python script of the proposed extraction method using LM algorithm with the extracted initial guess values is given in Fig. 3 [18]. In this program, the measurement data points are imported automatically from Excel table by using the python library "xlwings" [18].

B. Initial Guess parameters

The initial guess parameters of the optimization algorithm will be extracted by using the traditional extracted method based on experimental data. The initial value of channel-length modulation parameter λ is extracted using the slope of the *I-V* output characteristic at the saturation region as shown in Fig. 4. The initial values of parameters (V_T, dV_{TL}, K_{fl}, K_f, K_p, θ) are extracted in the same way introduced in [8], [11]. Selected points 1, 2 and 3 from transfer characteristic will be used to determine (V_T, dV_{TL}, K_{fl}, K_p, θ) initial parameters (Fig. 5). The initial value of linear region transconductance factor K_f is extracted from the slope of the output characteristic in linear region for low drain voltage [8], [11]. On the other hand, as noticed in power SiC MOSFET the drain current increases gradually from linear to saturation region. This effect is modeled by using P_{vf} parameter which is related to drain saturation voltage V_{DSAT}. In this work, the initial value of P_{vf} is determined from the extracted drain saturation voltage V_{DSAT}. As shown in Fig. 6, V_{DSAT} is extracted from dI_{DS}/dV_{DS} curve. For high current region, the initial value of P_{vf} can be calculated by dividing V_{DSAT} by (V_{GS}-V_{TH}). The initial values of capacitance parameters are extracted from the measured terminal capacitances: the input terminal capacitance (C_{ISS}), the reverse terminal capacitance (C_{RSS}) and the output terminal capacitance (C_{OSS}). The interelectrode capacitances can be given by:

$$C_{GD} = C_{RSS} \tag{9}$$
$$C_{GS} = C_{ISS} - C_{RSS} \tag{10}$$
$$C_{DS} = C_{OSS} - C_{RSS} \tag{11}$$

Fig. 7 shows the selected regions used to extract the initial parameter values of the capacitances. C_{GD} capacitance parameters are extracted in accordance with the method introduced in [17]. The estimated initial values of C_{GD} parameters *B* and *D* are obtained for V_{DS} = 0 as shown in Fig. 7. Initial parameter values of *A* and *C* are extracted from the gate-drain terminal capacitance at high drain voltage. The initial value of the fitting parameter *a* can be extracted from the slope of C_{GD}-*V* curve at low V_{DS}. Initial values of C_{DS} parameters (C_{DS0}, *MD* and V_{JD}) can be extracted by using the commonly used methods described in [19]: the three-point *CV* method or the linear regression with fixed diffusion potential method. Finally, initial C_{GS} parameter value can be extracted from the electrical characteristics of reverse (C_{RSS}) and input (C_{ISS}) terminal capacitances: $C_{GS} = C_{ISS} - C_{RSS}$.

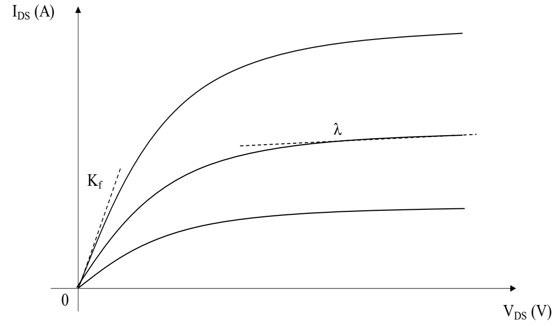


Fig. 4. Extraction of Kf and λ from the output characteristics

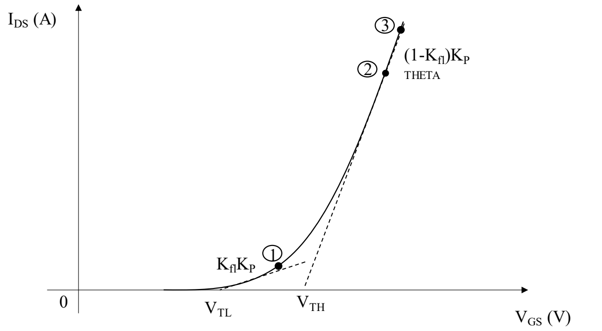


Fig. 5. Extraction of initial values of VT, dVTL, Kfl, Kp and θ from the IDS-VGS characteristic

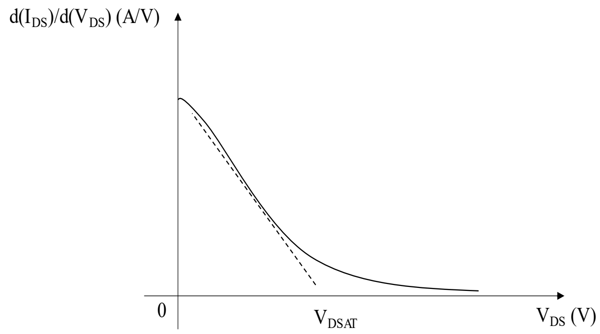
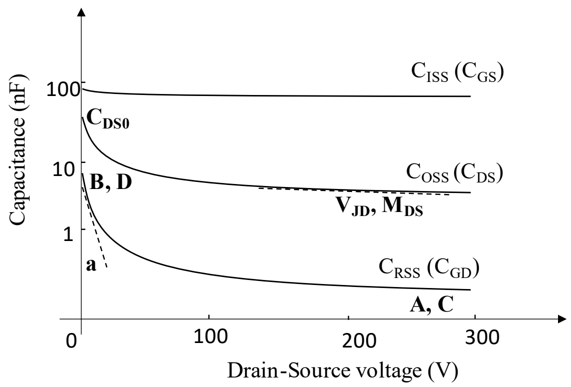


Fig. 6. Extraction of initial value of Pvf by using the output conductance



curve

Fig. 7. Extraction procedure of initial values of capacitance parameters from the terminal capacitances

TABLE I. extracted parameter values for the C2M1000170D Si MOSFET [20]

Parameter	Initial value	Optimized value	Unit
V_T	6.7	6.95	V
K_p	0.6	1.14	A/V^2
θ	0.8	0.422	V^{-1}
K_f	3.35	4.19	--
K_{fl}	0.3	0.331	--
λ	0	0.0137	V^{-1}
P_{vf}	0.83	0.301	--
dV_{TL}	1.7	2.15	V
C_{GS}	220	204	pF
A (C)	23.5	24.77	pF
B (D)	40	41.7	pF
a	0.68	0.216	V^{-1}
C_{DS0}	150	116.64	pF
V_{JD}	1	3.794	V
MD	0.16	0.382	--

IV. RESULTS AND DISCUSSION

The model parameters are extracted with respect to the procedure introduced in section 3 by using data from measurements or device datasheet. Table 1 gives the model parameters extracted from device datasheet of the C2M1000170D SiC MOSFET [20]. The present model was implemented into PSPICE circuit simulator as a subcircuit using the previous model equations. The netlist of the present model is given at the end of this paragraph.

Fig. 8 shows the simulated transfer characteristic compared with datasheet. Good agreement is obtained which confirms the accuracy of model simulations using the extracted model parameters. Fig. 9 shows the simulated output characteristics of the C2M1000170D N channel SiC power MOSFET in comparison with device datasheet at different junction temperatures (-55°C, 25°C and 150°C). The proposed parameter extraction method leads to very good agreements between the model and output characteristic curves provided from device datasheet.

On the other hand, the present model describes accurately all regions of operation thanks to its proper drain current equations. The datasheet curves and the simulated static reverse, input and output terminal capacitances of the C2M10017D SiC MOSFET are shown in Fig. 10. It can be seen that good agreement between the simulated and datasheet capacitance curves is obtained which validated the proposed parameter extraction method.

In Fig. 11, the simulation of output characteristics using the present model are compared with model [11] and measurements [11] at 25°C and 100°C. Unlike the traditional parameter extraction method proposed in [11], the method presented in the present work provide good agreement between simulations and experimental data. Finally, Fig. 12 gives the SPICE netlist corresponding to the present model.

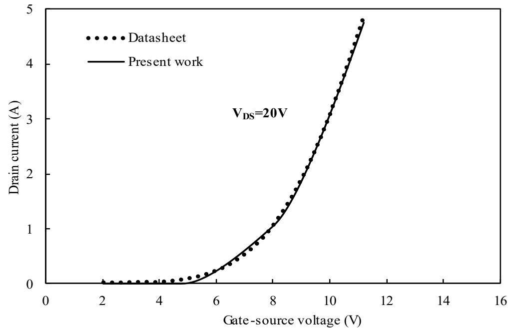


Fig. 8. Comparison in transfer characteristics between: simulation (pr sent work) and device datasheet at 25 °C

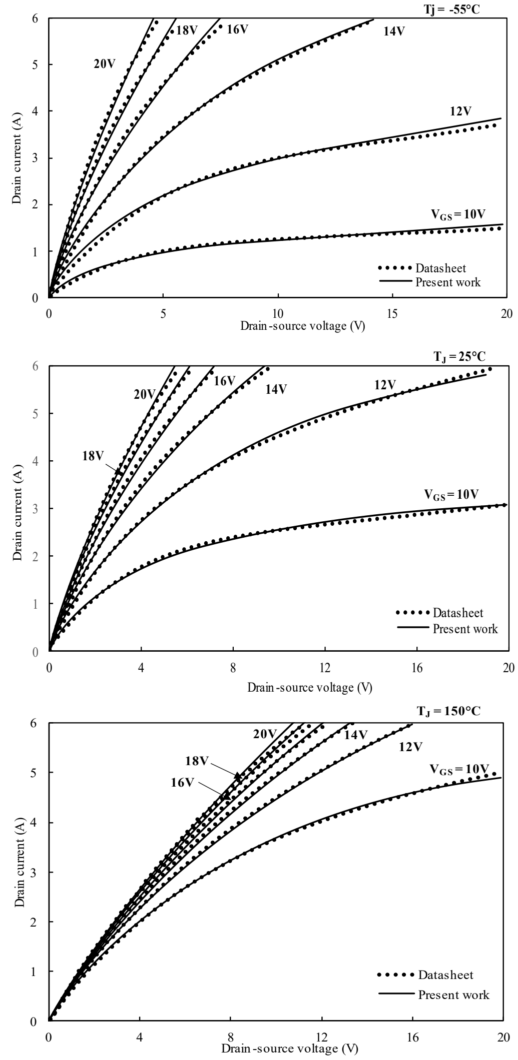


Fig. 9. Comparison in output characteristics between: simulation (present work) and device datasheet MOSFET at -55°C, 25°C and 125°C

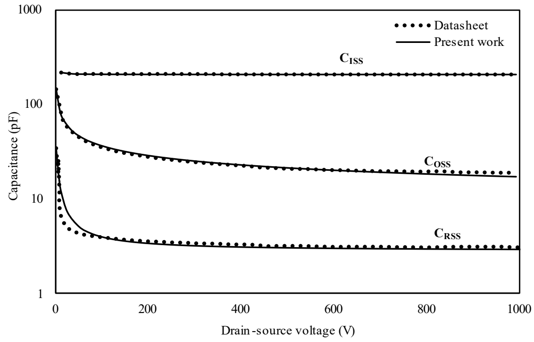


Fig. 10. Capacitance versus drain-source voltage: comparison between: simulation (present work) and device datasheet

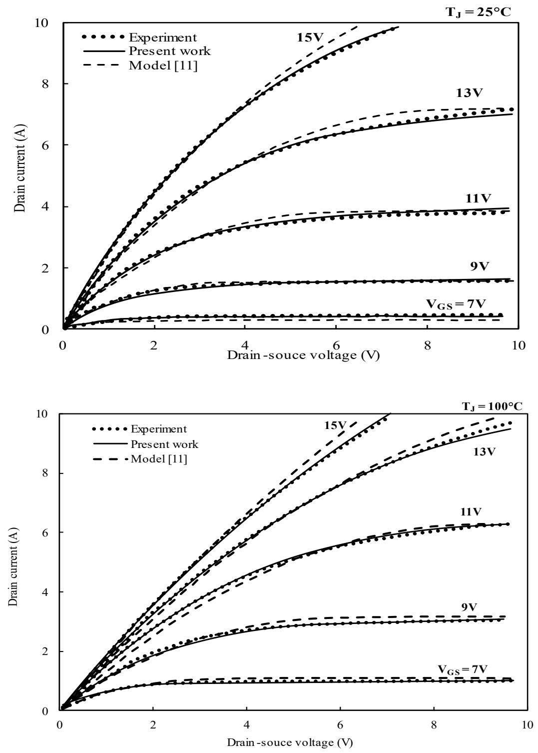


Fig. 11. Comparison in output characteristics between: simulation (pr sent work), and measurement from [11] at 25°C and 100°C

```
Title: Netlist for Model in this work
.SUBCKT   SiCMOSFET   g   d   s
.Param VT=, KP=, THETA=, KF=, KFL=, LAMBDA=, PVF=, DVTL=
.Param CGS=, as=, C=, D=, A=, B=
.Param VTL={VT-DVTL}, VTH={VT+(DVTL*KFL/(1-KFL))},
+y={KF/(KF- (PVF/2))}
.FUNC Idllin(Vds,Vgs) {KFL*KF*KP*((Vgs-VTL)*Vds-(((PVF^(y-
+1))*(Vds^y)*((Vgs-VTL)^(2-y)))/y))*(1+LAMBDA*Vds)
+/(1+THETA*(Vgs-VTL))}
.FUNC Idlsat(Vds,Vgs) {0.5*KFL*KP*((Vgs-
+VTL)^2)*(1+LAMBDA*Vds)/(1+THETA*(Vgs-VTL))}
.FUNC Idhlin(Vds,Vgs) {(1-KFL)*KF*KP*((Vgs-VTH)*Vds-(((PVF^(y-
+1))*(Vds^y)*((Vgs-VTH)^(2-y)))/y))*(1+LAMBDA*Vds)
+/(1+THETA*(Vgs-VTH))}
.FUNC Idhsat(Vds,Vgs) {0.5*(1-KFL)*KP*((Vgs-
+VTH)^2)*(1+LAMBDA*Vds)/(1+THETA*(Vgs-VTH))}
.FUNC VdsatLow(Vgs) {(Vgs-VTL)/PVF}
.FUNC VdsatHigh(Vgs) {(Vgs-VTH)/PVF}
.FUNC IdL(Vds,Vgs) {IF(Vgs-VTL<=0,0,IF(Vds-
+VdsatLow(Vgs)<=0,Idllin(Vds,Vgs),Idlsat(Vds,Vgs)))}
.FUNC IdH(Vds,Vgs) {IF(Vgs-VTH<=0,0,IF(Vds-
+VdsatHigh(Vgs)<=0,Idhlin(Vds,Vgs),Idhsat(Vds,Vgs)))}
.FUNC Ids(Vds,Vgs) {IdL(Vds,Vgs)+IdH(Vds,Vgs)}
GMOS   d   s   value {Ids(V(d,s),V(g,s))}
.FUNC QGS(Vgs) {Vgs*CGS}
G-Cgs g s value={DDT(QGS(V(g,s)))}
Dbody s d Dbody
.model Dbody D(M=  CJO=  VJ=)
.FUNC CGD(Vgs,Vds) {IF(Vgs-Vds<=0,C*(ATAN(as*(Vgs-
+Vds)))+D,B*(TANH(a*(Vgs-Vds)))+C)}
.FUNC QGD(Vgs,Vds) {(Vgs-Vds)*CGD(Vgs,Vds)}
G-Cgd g d value={DDT(QGD(V(g,s),V(d,s)))}
.ends
```

Fig. 12. Netlist of the present model

V. CONCLUSION

An improved parameter extraction method for SiC power MOSFET model was presented. This method combines the traditional extraction method with the nonlinear least square optimization algorithm. The description of the proposed method with its implementation in Python programming language has been included in the present paper. The parameter extraction method was validated by the excellent agreement obtained between simulations and experiment data over the entire operating regions of the SiC power MOSFET device. Finally, results confirm that the described extraction method is very useful to improve SiC power MOSFET models by the accurately extracted parameters.

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