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A variable-temperature parameter model for SiC MOSFETs considering parasitic parameters

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Abstract: *In recent years, silicon carbide MOSFET has been widely used in switching power supply, electric vehicle and grid-connected inverter. In order to accurately predict the switching characteristics of silicon carbide MOSFET in the design stage, it is necessary to establish an accurate silicon carbide MOSFET model. In this paper, a continuous function is used to describe the static characteristics of MOSFET. Secondly, a parasitic parameter extraction method based on two-port S-parameter measurement is used to extract the parasitic parameters of MOSFET introduced by packaging and other factors, and consider the nonlinear characteristics of interstage capacitance. Finally, a double-pulse experimental platform was set up to verify the accuracy of the established model. The experimental results show that the established model can reflect the working condition of MOSFET in actual conditions with high accuracy.*

Keywords: *Parasitic parameter, Silicon carbide MOSFET, Temperature parameter, Behavior model*

1. Introduction

With the maturity of the design and manufacturing process of SiC MOSFET devices, the price of SiC devices is gradually decreasing, and it is widely used by virtue of its advantages of high frequency, low loss and high temperature resistance. In the product development stage, in order to verify the circuit topology and reliability, the system is usually simulated to evaluate the operating efficiency and electromagnetic compatibility characteristics of the system. Therefore, the establishment of an accurate simulation model of SiC devices is of great significance to scientific research and engineering applications. Domestic and foreign scholars have conducted in-depth studies on this issue.

Wang et al. predicted the dynamic characteristics of SiC MOSFET by describing the parasitic parameters inside the device, taking into account the change of on-resistance with temperature and nonlinear capacitance[1]. Karus et al. established a compact model of SiC MOSFET based on physical devices, and embedded the temperature change model of semiconductor inside the device[2]. Some scholars use finite element analysis tools to solve the semiconductor physical equation of the device, and at the same time add the functional relationship between the device material and temperature into the equation, so that it can accurately describe the switching process of SiC MOSFET. However, the semiconductor equation has too many parameters and complex solving process, which is difficult to apply to system-level simulation[3-4]. In order to seek a more efficient modeling method, some scholars have established a SiC MOSFET behavioral circuit model based on SPICE Level 1 model. Tools such as PSpice and Simplorer are used to describe the static characteristics (output characteristic curve, transfer characteristic curve, on-resistance and threshold voltage, etc.) and dynamic characteristics (nonlinear capacitance and internal parasitic parameters, etc.) of SiC MOSFET[5-7].

In this paper, the static characteristics of silicon carbide MOSFET are firstly fitted with temperature parameters. A continuous function is used to describe the output characteristic curve and the transfer characteristic curve, and the parameters are set as a function of temperature. Secondly, a method based on two-port S-parameter is used to extract the parasitic parameters of SiC MOSFET to describe the switching characteristics of sic MOSFET. Finally, the accuracy of the established model is verified.

2. Static behavior modeling of SiC MOSFET considering temperature effect

The static characteristics of SiC MOSFET mainly include transfer characteristic curve and output characteristic curve, which define the voltage and current relationship of SiC MOSFET in working state,

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and are the basis of static characteristic modeling. In this chapter, a continuous function is used to model the static characteristics of SiC MOSFET on the basis of EKV model, and the influence of temperature on threshold voltage is corrected.

2.1. Static property modeling and parameter fitting based on improved EKV model

Traditional EKV model is suitable for high-frequency circuits and RF applications and takes into account non-ideal factors such as temperature change. However, due to the large temperature change in the operating range of SiC MOSFET, the EKV model proposed based on silicon-based devices cannot well describe the temperature characteristics of silicon carbide devices. Meanwhile, in the traditional EKV model, in order to describe the actual physical parameters. The model is complicated and difficult to converge. Therefore, the traditional EKV model is improved, two controlled sources are combined with a continuous function to describe the output characteristics and transfer characteristics at the same time, and temperature is directly added as a variable, that is, drain current I_d is controlled by temperature T, drain-source voltage V_{ds} and gate source voltage V_{gs} at the same time, as shown in Equation (1):

$$I_d = \begin{cases} 0, & V_{gs} < V_{th} \\ I_d(V_{ds}, V_{gs}, T), & V_{gs} > V_{th} \end{cases} \tag{1}$$

The threshold voltage V_{th} in equation (1) is also a function of temperature. In traditional models, linear functions are usually used to fit the change of threshold voltage. In order to broaden the temperature range described by the model, cubic polynomials are used in this paper to fit the threshold voltage, and the fitting equation is as follows:

$$V_{th} = k_1 T^3 + k_2 T^2 + k_3 T + k_4 \tag{2}$$

The comparison between the fitting results and the data book is shown in Figure 1:

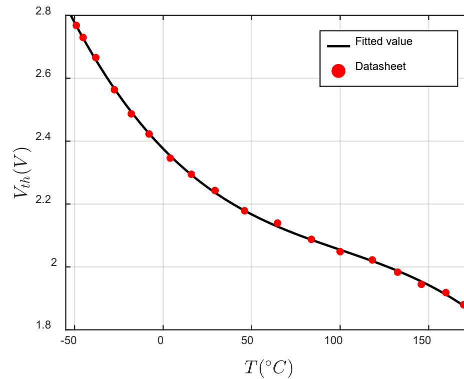

Figure 1: Threshold voltage fitting.

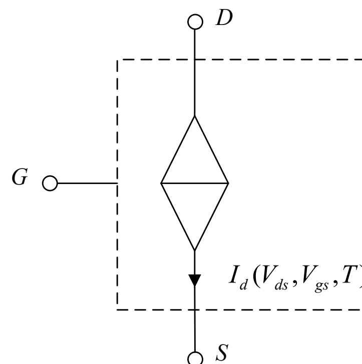

Figure 2: SiC MOSFET Controlled current source.

The expression of the SiC MOSFET core controlled current source constructed in this paper is shown in Figure 2. According to the image trend of SiC MOSFET output characteristics and transfer characteristics, and to ensure that the construction function can accurately describe its static

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characteristics and meet the changes of the function curve under different temperature and voltage conditions, the improved controlled current source in this paper is represented by equation (3):

$$I_d = (p_1 + p_2 * V_{ds} + p_3 * V_{gs} + p_4 * V_{ds}^2 + p_5 * V_{gs}^2 + p_6 * V_{ds}^3 + p_7 * V_{gs}^3 + p_8 * V_{ds} * V_{gs} + p_9 * V_{ds}^2 * V_{gs} + p_{10} * V_{ds} * V_{gs}^2) * (p_{11} * V_{ds} * V_{gs}) + p_{12} \tag{3}$$

Where is the fitting parameter and each parameter is a function of temperature, this paper sets it as a quadratic function of temperature, it is expressed by equation (4):

$$Param(T) = k_1 T^2 + k_2 T + k_3 \tag{4}$$

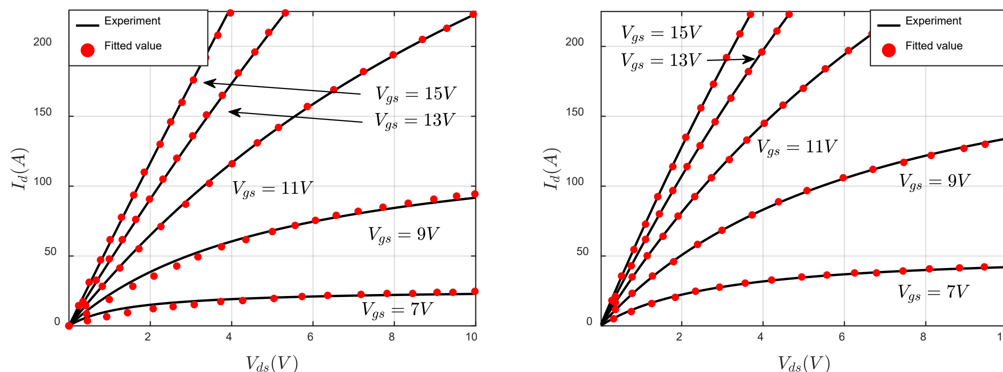
According to the obtained formula of controlled current source, the global optimization algorithm is used to optimize and fit the extracted SiC MOSFET characteristic curve data. The global optimization algorithm does not need to provide the initial value during fitting, and the fitting speed is fast and the precision is high. It should be noted that when data points are taken, points are taken uniformly where the curve is flat, and points are taken densely where the curve slope changes greatly. After optimization and fitting, the values of static characteristic parameters at different temperatures are shown in Table 1:

Table 1: Static feature parameter value.

Parameter	T=-40℃	T=25℃	T=175℃
P_1	291441.698	-3.91913	69638.40489
P_2	21301.34648	0.159742	-695.85754
P_3	6110.60742	0.988187	-24945.55337
P_4	-526.77545	0.003334	-304.87237
P_5	-19256.76434	-0.04848	1654.52098
P_6	-79.94576	-6.40e-05	8.45223
P_7	802.98546	0.000599	-28.80725
P_8	2430.39185	2.237928	1179.74458
P_9	118.38999	0.138155	0.69006
P_{10}	-145.26349	0.00015	-68.02357
P_{11}	-3.36201E-06	-0.05497	-0.00011
P_{12}	-0.43605	0.002634	-0.356373

2.2. Static characteristic verification

In order to verify the accuracy of the static model of SiC MOSFET built in this paper, Wolfspeed's C3M0015065D SiC MOSFET was selected to verify the output characteristics and transfer characteristics. In this paper, -40℃, 25℃ and 175℃ were selected as the test temperatures, and the gate-source voltage was set at 7-15V. During the transfer characteristic test, the drain-source voltage is set to 20V, and the gate-source voltage changes linearly to observe the drain current. The transfer characteristic and output characteristic curves at different temperatures are shown in the figure. The analytical working plane of the established model at different temperatures is shown in Figure 2.



(a) Output characteristic curve, T=-40℃ *(b) Output characteristic curve, T=-40℃*

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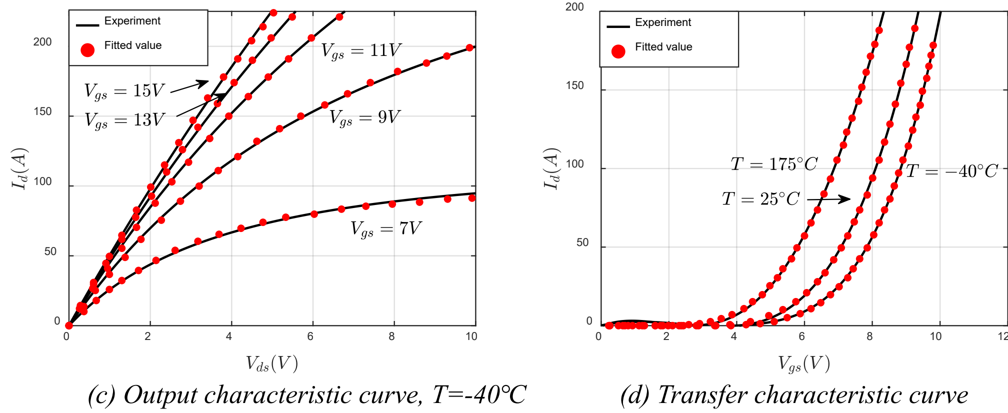

(c) Output characteristic curve, T=-40℃ *(d) Transfer characteristic curve*

Figure 3: Static characteristic verification.

As can be seen from Figure 3, in the working plan constructed by equation (3) at different temperatures, the data points fit well with the analytical plane, and the static characteristics of the established model can better describe the output characteristics and transfer characteristics of SiC MOSFET at different temperatures.

3. Modeling dynamic characteristics of SiC MOSFET

3.1. Parasitic parameter extraction method

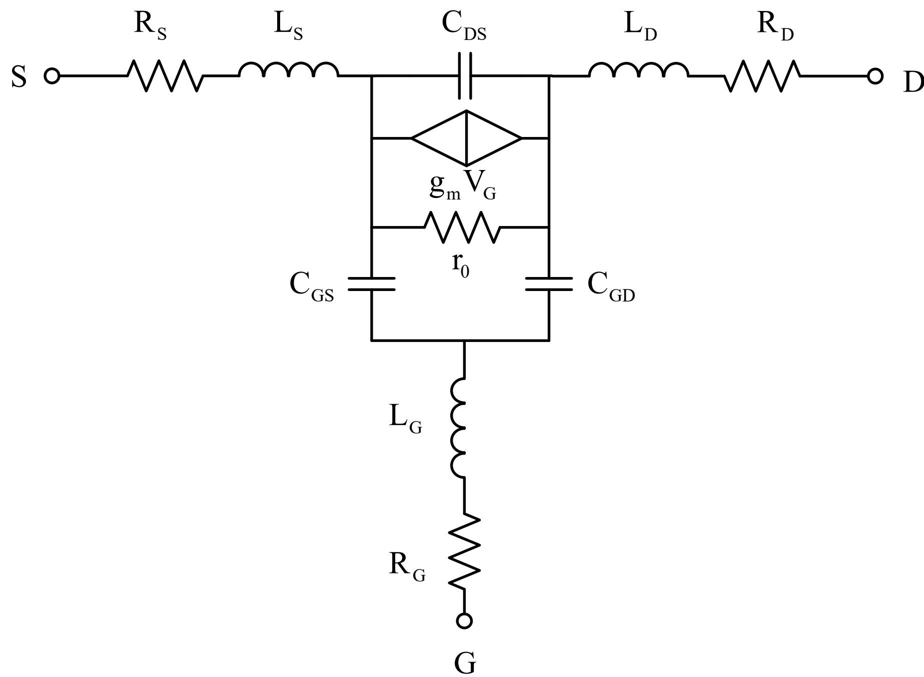

Figure 4: SiC MOSFET small signal model.

Generally, MOSFET can be established as a small signal equivalent model as shown in Figure 4, where C_{gs}, C_{ds} and C_{gd} are interstage capacitors, R_s, R_d and R_g are parasitic resistors of three pins, L_s, L_d and L_g are parasitic inductors of three pins, and constant current source V_G is used to simulate the change of drain current with gate voltage. Due to the channel length modulation effect, the drain current increases with the drain-source voltage, and the equivalent output resistance can be calculated as $r_o = \Delta V_{ds}/\Delta I_d$, where ΔV_{ds} represents the gate-source voltage change rate and ΔI_d represents the drain current change rate[8].

Small signal equivalent model of MOSFET In the case of zero voltage bias, that is, drain current, the controlled current source in the established small signal model can be regarded as a break, and the

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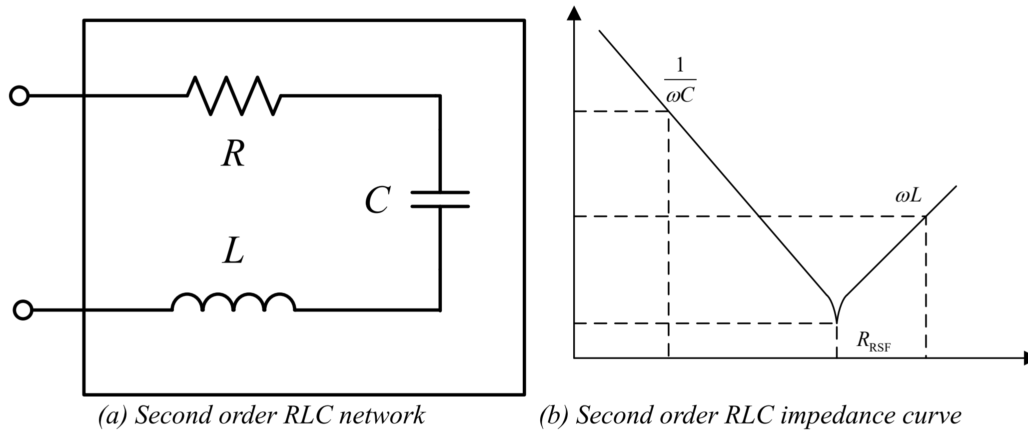
equivalent resistance value of infinity can also be regarded as a break, as shown in Formula (5) and (6):

$$r_0 = \Delta V_{\mathrm{ds}} / \Delta I_{\mathrm{d}} = \infty \tag{5}$$

$$I_d = 0 \tag{6}$$

In this paper, the equivalent small signal model in the case of zero voltage bias is regarded as a two-port model, with gate and drain as one port and gate and source as the other port. Vector network analysis is used to measure the S-parameters of the two ports and then convert them into Z parameters through the conversion formula. Each parameter Z11, Z12, Z21, and Z22 in the Z matrix of a two-port network will display a second-order RLC circuit consisting of a series combination of inductors, capacitors, and resistors, as shown in Figure 5(a), and a typical impedance characteristic curve of a second-order series RLC circuit is shown in Figure 5(b).



(a) Second order RLC network *(b) Second order RLC impedance curve*

Figure 5: Second-order networks and impedance characteristics.

In Figure 5(b), the frequency-dependent impedance is the smallest at the self-resonant frequency, where the capacitance and inductor impedance are the same, and the port exhibits pure resistance. The resistance R can be calculated based on the measured port impedance. When the frequency is much higher than the self-resonant frequency, the inductive impedance plays a dominant role, which can be calculated by approximate formula (7). When the frequency is much lower than the self-resonant frequency, the capacitance plays a dominant role, which can be calculated by an approximate formula (8).

$$L = (\left|Z_{(f)}\right| / 2\pi f)_{f \gg f_{\mathrm{SRF}}} \tag{7}$$

$$C = 1 / (2\pi f \left|Z_{(f)}\right|)_{f \ll f_{\mathrm{SRF}}} \tag{8}$$

Therefore, the steps for extracting parasitic parameters of MOSFET based on the two-port S parameter are as follows: First, the dual-port S-parameter of the MOSFET is measured at 10K-500MHz and the S-parameter is converted to the Z parameter. Then, the capacitance C_{ds}, C_{gs} and C_{gd} of Z parameters of each two-port network are solved. Next, the inductance L_{s}, L_{d} and L_{g} of Z parameter of each two-port network are solved. Finally, the resistance R_{s}, R_{d} and R_{g} are solved according to the harmonics.

3.2. The extracted values are compared with the actual values

Wolfspeed's C3M0015065D was used to extract parasitic parameters, and vector network analyzer was used to measure SiC MOSFETS parameters. To ensure the accuracy of the experiment, the network analyzer needs to be calibrated before using the appropriate amount of network analyzer. The cable connected to the reception device is calibrated with the standard impedance 50 calibration head to eliminate cable errors. The comparison between the extracted results and the reference values provided by the manufacturer is shown in Table 2. The comparison between the Z parameters generated by the extracted parasitic parameter values and the measured Z parameters of the back-band MOSFET small signal model is shown in Figure 6.

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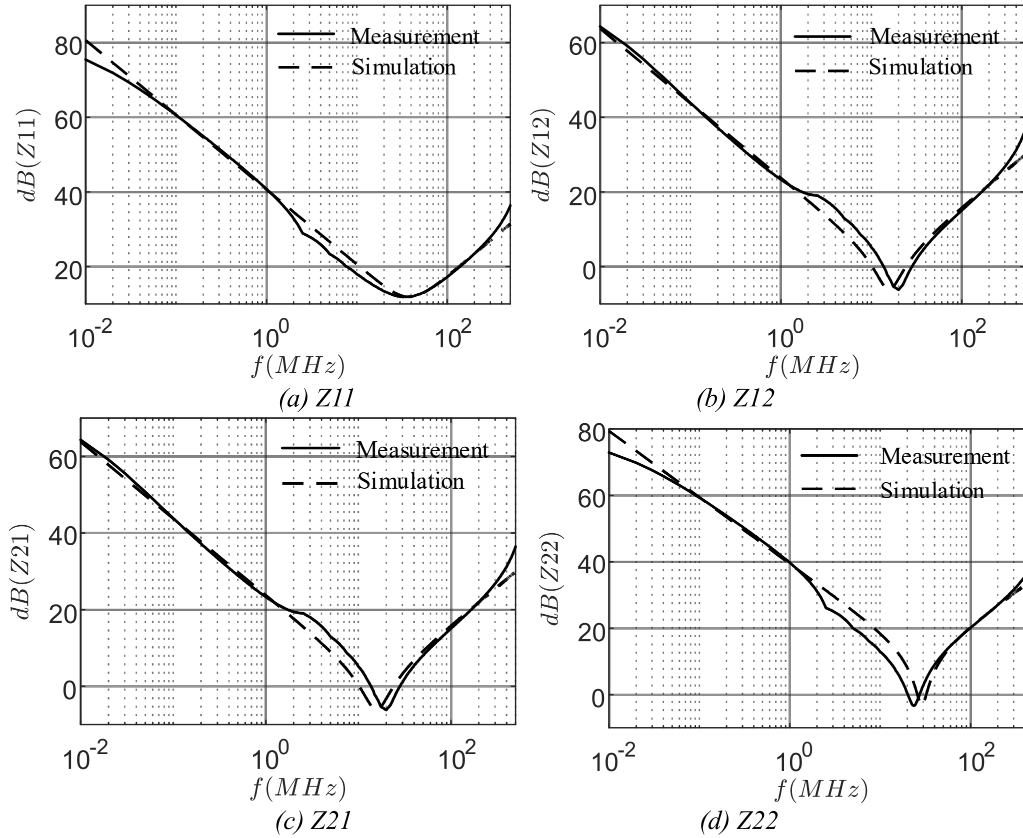

Figure 6: Comparison between the measured Z parameter and the simulated Z parameter.

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Parameter	Datasheet	Extract value	Error
C_{gs}(nF)	1.25	1.264	1.12%
C_{gd}(nF)	1.50	1.491	0.6%
C_{ds}(nF)	0.25	0.249	0.4%
L_s(nH)	1.80	1.892	5.1%
L_d(nH)	7.80	7.865	0.83%
L_g(nH)	11.0	9.992	9.1
R_s(Ω)	3.50	3.441	1.6%
R_d(Ω)	0.20	0.188	6%
R_g(Ω)	0.50	0.491	1.8%

The dashed line in Figure 6 represents the Z parameter generated by the small signal model generated by the parasitic parameter value obtained from the measurement calculation back to the simulation software, and the solid line represents the Z parameter measured by the vector network analyzer. The comparison results show that the extraction results are only slightly deviated at the resonance point, and the curves of low frequency band and high frequency band are highly consistent, which proves that the method has high extraction accuracy. Table 2 shows the comparison between the parasitic parameter values extracted by this method and those in the manufacturer's data table. It can be seen from the table that the extracted parasitic parameter values obtained through the above extraction steps are more accurate, and the maximum error is 9.1% compared with the reference value, indicating that this method can be used to extract parasitic parameters of MOSFET quickly and accurately.

3.3. Dynamic performance verification

In order to verify the accuracy of dynamic characteristic modeling, a dual-pulse simulation test circuit was built in LTspice, and the test conditions were: DC voltage 500V and bus current 20A. The switch waveform of the model established in this paper is compared with the actual curve provided by the manufacturer, as shown in Figure 7:

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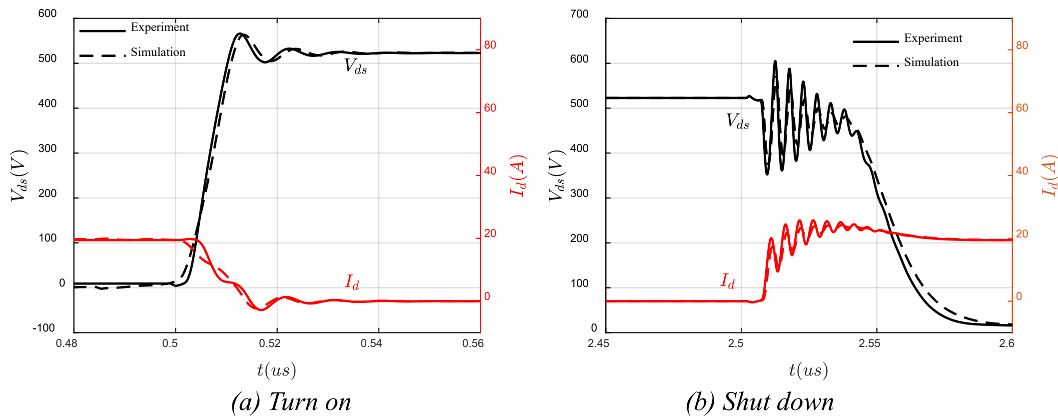

(a) Turn on *(b) Shut down*

Figure 7: Comparison of switching waveforms.

As can be seen in Figure 7, the waveforms of drain-source voltage and drain current are in good agreement with those provided by the manufacturer. During the shutdown process, the drain current correctly reflects the gradual reduction of the current oscillation to zero. During the turn-on process, the leak-to-source voltage and drain current oscillation amplitude of the dynamic model are slightly higher than those of the simulation experiment, which may be caused by the spurious parasitic parameters taken into account in the circuit, and the drain-source voltage is delayed. Due to the difficulty of fully considering the spurious parameters and parasitic parameters of the circuit, the dynamic behavior model established in this paper is somewhat different from the simulation, but in general, the established model can correctly describe the voltage and current overshoot oscillation behavior during the turn-on and turn-off process, and the established model has good accuracy and can be used to describe the switching characteristics of SiC MOSFETs.

4. Conclusions

Firstly, based on the improved EKV model, a continuous function is used to describe the static characteristics of the MOSFET under the influence of temperature, and the influence of the threshold voltage is corrected according to the temperature, and three different temperatures of -40°C, 25°C and 175°C are selected to verify the accuracy of the static characteristics of the established model. Secondly, a parasitic parameter extraction method based on two-port S-parameter measurement is used to extract the parasitic inductance and parasitic resistance of MOSFET. Finally, a double-pulse experimental platform was built to verify the accuracy of the model. Experimental results show that the established model can reflect the working conditions of MOSFETs in real conditions and has high accuracy.

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