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A Short-circuit Model Based on Artificial Neural Network and Artificial Bee Colony Algorithm for SiC MOSFETs

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Research Article

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A Short-circuit Model Based on Artificial Neural Network and Artificial Bee Colony Algorithm for SiC MOSFETs

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Abstract A short-circuit model for silicon carbide (SiC) metal-oxide semiconductor field effect transistors (MOSFETs) using hybrid modeling method based on artificial neural network (ANN) and improved artificial bee colony (ABC) algorithm is proposed in this paper. In order to improve the search ability of the ABC, particle swarm optimization (PSO) is introduced to the scout bees' search strategy. The improved ABC is employed to find suitable initial parameters for ANN model, which can improve the accuracy of modeling results. Based on hybrid modeling method, the normal working model of SiC MOSFETs is established first. The modeling results of $I-V$ characteristics, $C-V$ characteristics and small signal parameters (g_m, g_d, etc.) are in good agreement with datasheet, which fully demonstrates the validity of the normal working model. Then the short-circuit model of SiC MOSFETs is further obtained based on the relationship between short-circuit current and junction temperature and normal working model. Eventually, the proposed short-circuit model is verified by device- and circuit-level tests. With its precision and simplicity, the proposed short-circuit model can be used to analyze short-circuit faults in SiC MOSFET simulation circuits and provide assistance for the design of protection circuits.

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Keywords artificial bee colony (ABC) algorithm · artificial neural network (ANN) · silicon carbide (SiC) metal-oxide semiconductor field effect transistors (MOSFETs)

1 Introduction

With the rapid development of process technologies of silicon carbide (SiC), SiC metal-oxide semiconductor field effect transistors (MOSFETs) have been commercialized in mass production and are popular in the design of high-power electronics [1]. Compared with traditional Si MOSFETs, SiC MOSFETs have lots of outstanding advantages, such as higher switching speed, higher switching frequency, smaller ON-state resistance, and better high temperature stability [2]. Due to the excellent characteristics of SiC MOSFETs, they are often used in harsh circuit conditions. Hence, it is necessary to ensure its reliability and safety to guarantee that SiC MOSFETs can operate normally under harsh conditions. One of the key reliability issues is the short-circuit capability of the SiC MOSFETs [3]. Therefore, an accurate and simple SiC MOSFET short-circuit simulation model is urgently needed to predict the characteristics of the faults caused by the short-circuit and provide guidance for the design of protection circuits.

In the past few decades, many SiC MOSFET models [4–6] have been proposed, but most of them only consider normal working scenarios. Recently, several models [7–9] describing the short-circuit characteristics of SiC MOSFETs have been reported. Physics-based models [7] can describe the internal physical characteristics of SiC MOSFETs and are usually considered to be accurate, but they are too complex to be suitable for power electronic circuit simulation [10]. The

PSpice short-circuit model of SiC MOSFETs [8,9] is simpler than the physics-based model, but it still has many parameters. The extraction of parameters is time-consuming and may lead to inaccurate results. In addition, the PSpice model only considers the short-circuit situation when the case temperature is 25℃, but different case temperatures have an impact on the short-circuit current. Data-oriented modeling methods can be quickly applied for the newly generated device data. Artificial neural network (ANN) is considered as a data-oriented modeling method [11] and can achieve an accurate model in a short time, which has been employed in the modeling of semiconductor devices [12,13]. In order to reduce the developing time and obtain an accurate model, a short-circuit model of SiC MOSFETs considering case temperatures based on ANN is proposed in this paper.

In this work, a Multi-layer perceptron (MLP) [14] based on the levenberg-marquardt (LM) algorithm [15] is adopted to establish a short-circuit model for SiC MOSFETs. Since the LM algorithm is quite sensitive to the initial values, for the sake of overcoming the sensitivity of the LM to the initial values and get better modeling results, an improved artificial bee colony (IABC) algorithm [16] combined with particle swarm optimization (PSO) [17] (IABCPSO) is proposed and introduced into the training of MLP to find the appropriate initial weights and biases for the LM. In this paper, we first build the SiC MOSFET model under normal working conditions, and then the short-circuit model is developed based on the normal working model and junction temperature. A SiC MOSFET of type C2M0080120D (1200V/36A) [18] is chosen as the modeling object in this paper. Furthermore, the accuracy of the short-circuit model based on this hybrid modeling method is verified by both the device and circuit-level tests.

2 Normal Working ANN Model

Since the drain-source current I_{ds} under normal operating conditions also contributes to the short-circuit current, it is first modeled based on ANN modeling method, which takes into account the temperature characteristics. The ANN model contains the drain-source current I_{ds}, body diode D_b, gate-drain capacitor C_{gd}, gate-source capacitor C_{gs}, drain-source capacitor C_{ds} and internal gate resistor R_g, as shown in Fig. 1.

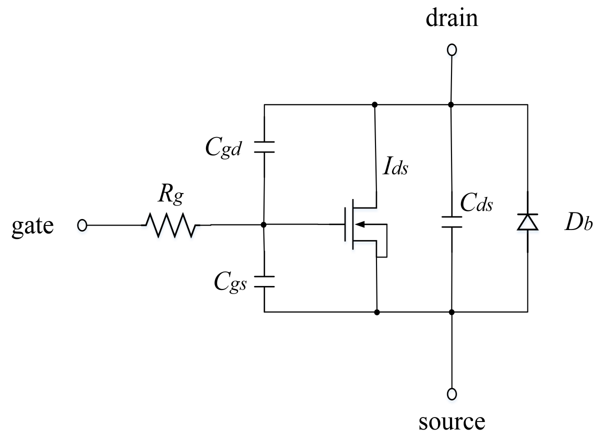

Fig. 1 The ANN model of SiC MOSFET

2.1 Improved artificial bee colony algorithm combined with particle swarm optimization

In our previous work [19], we used the MLP based on the LM algorithm for modeling SiC MOSFETs, which is also adopted as the basis of this paper. Different from [19], the ABC algorithm in this paper is improved by introducing PSO into the search strategy of the scout bees.

In PSO [17], each particle represents a possible solution, and the optimization process of the particle is related to two important factors: the individual optimal solution (p_{best}) and the swarm's optimal solution (g_{best}). And the fitness function of PSO will guide the particle swarm to find the optimal solution. In this paper, PSO is introduced into the optimization process of the scout bees of ABC. When the employed bees and onlooker bees are converted to scout bees because their corresponding nectar sources aren't updated in the limited times, they will restart the search for the best solution in the entire range set at the beginning, which is undoubtedly a waste of current information resources, such as the current best solution of the entire bee colony (X_{best}) found by the employed bees and the onlooker bees. After introducing PSO into the optimization process of the scout bees, we can effectively use the X_{best} information, and the optimization of the scout bees will be carried out in accordance with the idea of PSO, thereby improving the efficiency of the whole algorithm. The optimization process of the scout bees can be described as:

$$N_{ij} = w \cdot N_{ij} + r_{i1} \cdot c_1 (p_{best} - M_{ij}) + r_{i2} \cdot c_2 (g_{best} - M_{ij}) \quad (1)$$

$$M_{ij} = M_{ij} + N_{ij} \quad (2)$$

where N_{ij} and M_{ij} represent the velocity and position of the ith particle, respectively; w is an inertia factor

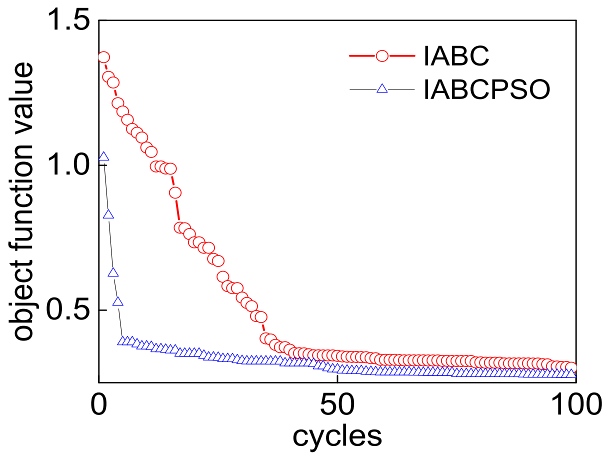

Fig. 2 Comparison results between IABCPSO and IABC

describing the contribution rate of the particle's previous speed to its current speed, which helps particles to search a wider area in the previous direction. Moreover, r_{i1} and r_{i2} are two random numbers in the range of [0,1]; c_1 and c_2 are the acceleration factors. In order to use the X_{best} information, we set M_i as:

$$M_i = X_{best}. \tag{3}$$

Then, the particle swarm will use X_{best} as the initial position to help scout bees search for the best solution, which effectively enhances the search ability of the whole algorithm. After that, the mean square error of the I-V modeling results and the datasheet is set as the fitness function, and we compared modeling results of IABCPSO and IABC in [19] running 100 times respectively, the results of which are shown in Fig. 2. The conclusion can be drawn from Fig. 2 that, IABCPSO can get better results in a shorter time, which confirms the effectiveness of our proposed algorithm in this paper.

2.2 The hybrid algorithm

After the IABCPSO algorithm is implemented, we combine it with LM-based MLP to model the SiC MOSFETs. Both LM and IABCPSO use mean square error as the objective function. IABCPSO first finds the appropriate initial weights and biases for LM, which overcomes the sensitivity of LM to the initial values. Then, MLP will use the fast convergence characteristics of LM to complete the training in a short time, and obtain a model with high accuracy and good generalization. Figure 3 plots the flow chart of this hybrid algorithm.

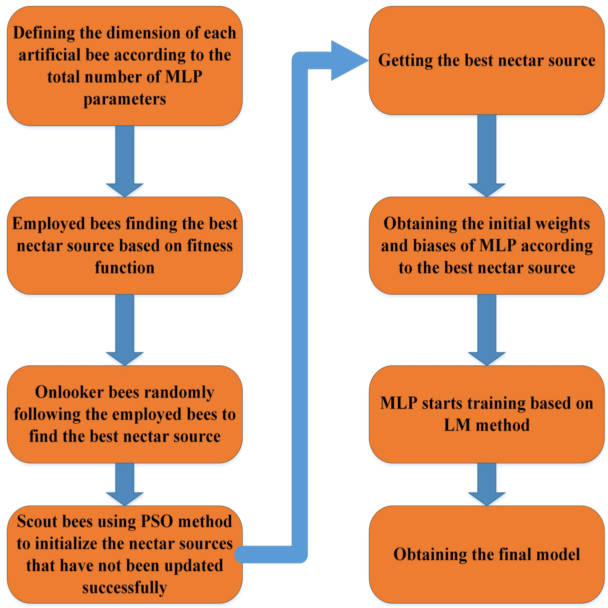

Fig. 3 The flow chart of a hybrid algorithm based on MLP and IABCPSO

2.3 Modeling of drain-source current I_{ds}, body diode D_b and internal capacitors

In this paper, the drain-source current I_{ds}, body diode D_b and internal capacitors are all modeled using our proposed hybrid modeling method (IABCPSO-MLP). According to I-V curves provided by datasheet [18], the drain-source current I_{ds} can be modeled by an ANN with three inputs (drain-source voltage V_{ds}, gate-source voltage V_{gs}, and operating temperature T). In order to obtain a high-precision model, we use an ANN containing two hidden layers to model I_{ds} and each layer contains 8 neurons. The final modeling results can reach an accuracy of more than 99%.

From datasheet [18], we can find that the current of body diode I_{sd}, like I_{ds}, varies with V_{ds}, V_{gs}, and T. Therefore, the modeling of I_{sd} adopts the same ANN structure as that of I_{ds} and the accuracy of modeling results of I_{sd} can also reach more than 99%.

According to the datasheet [18], both C_{ds} and C_{gs} vary nonlinearly with one variable, i.e. V_{ds} or V_{gs}. Hence, C_{ds} and C_{gs} can be modeled by same MLP structure with one input (V_{ds} or V_{gs}) and one output (C_{ds} or C_{gs}). Considering the simplicity and accuracy, the 1-5-5-1 MLP structure is finally selected among many tested structures, the accuracy of which can reach 98%.

3 Short-circuit model of SiC MOSFETs

When the short-circuit faults occur, the circuit power loop impedance will become extremely small, and the

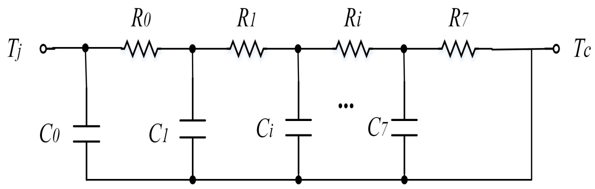

Fig. 4 Thermal network model between case and junction

short-circuit current I_{sc} of the SiC MOSFETs will rise to a large amount. As the current of the circuit is very large, the power loss P_{loss} at this time will also become very large. Therefore, the junction temperature T_j begins to increase, leading to decrease of the channel carrier mobility and I_{sc}. However, T_j is still increasing, and the leakage current caused by thermal ionization is also gradually increasing. When the leakage current rate generated by thermal ionization is higher than the decrease rate of carrier mobility, I_{sc} starts to rise again. It can be concluded that the change of the short-circuit current of the SiC MOSFETs is mainly caused by the change of T_j. Therefore, to establish a short-circuit model, the change curve of T_j during the short-circuit process should be obtained first.

3.1 Thermal network model

In order to obtain the change curve of T_j during the short-circuit process, the thermal network of the SiC MOSFETs is established. The thermal network model based on the case-to-junction thermal impedance formed by a resistance-capacitance (RC) network [9] is the most commonly used, which is also used in this paper. As shown in Fig. 4, T_c and T_j are the case and junction temperatures of SiC MOSFETs, respectively. R_i and C_i are the thermal resistance and thermal capacitance, respectively.

After the development of the thermal network model, the transient thermal impedance Z_{th} can be obtained by [9]:

$$Z_{th} = \sum_{i=1}^{n} R_i \cdot (1 - e^{-\frac{t}{R_i \cdot C_i}}). \tag{4}$$

The transient power loss P_{loss} is given by [9]:

$$P_{loss} = V_{ds} \cdot I_{ds}. \tag{5}$$

After getting P_{loss} and Z_{th}, the junction temperature T_j of SiC MOSFETs can be obtained, which can be expressed as [9]:

$$T_j = P_{loss} \cdot Z_{th} + T_c. \tag{6}$$

In this paper, the experimental data [20] is used as model reference. In [20], the DC bus voltage (V_{ds}) is set as 400V and the corresponding short-circuit current curves under different case temperatures are given. In Fig. 5, the change of T_j is shown for T_c=25℃ and V_{ds}=400V, which is obtained by Eq. (6) after substituting the transient power loss P_{loss}. When SiC MOSFETs work under normal conditions, the junction temperature is consistent with the case temperature, and when a short-circuit fault occurs, the junction temperature begins to rise.

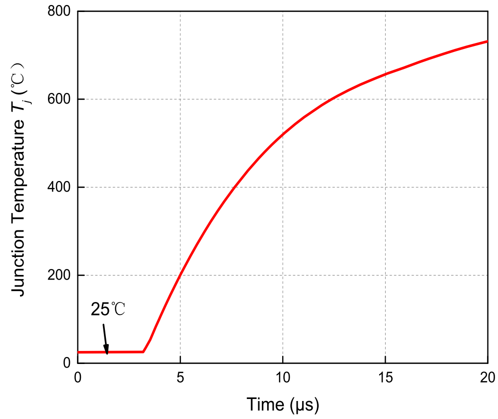

Fig. 5 The change curve of junction temperature T_j

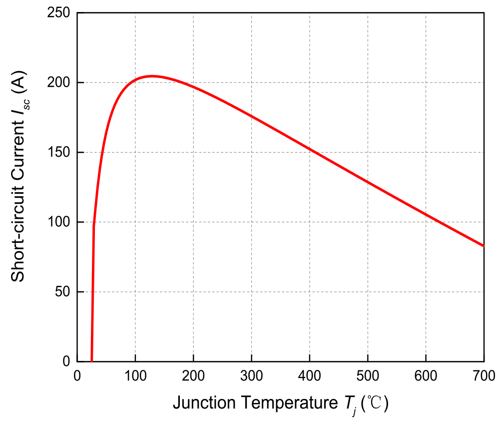

Fig. 6 The corresponding relationship between short-circuit current I_{sc} and junction temperature T_j

3.2 Modeling of short-circuit current I_{sc}

After getting the instantaneous change curve of T_j, we can acquire the relationship between I_{sc} and T_j, as shown in Fig. 6, where the short-circuit current I_{sc} can be fitted based on T_j. Since when the short-circuit fault occurs, the current I_{ds} under normal working conditions also has output, I_{sc} needs to be fitted based on I_{ds}.

In this paper, the impact of different case temperatures on the short-circuit current is considered. Since

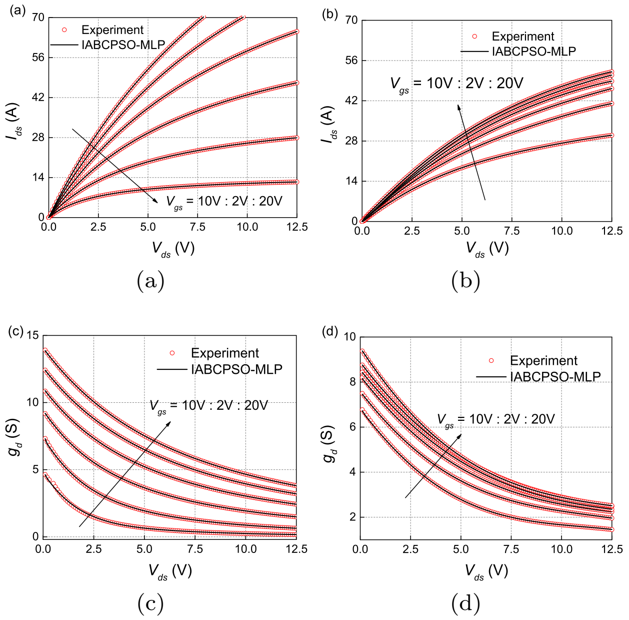

Fig. 7 The comparison results of output characteristics and output conductance between IABCPSO-MLP and datasheet under different temperatures. **a** Output characteristics under T=25℃. **b** Output characteristics under T=150℃. **c** Output conductance g_d under T=25℃. **d** Output conductance g_d under T=150℃

the relationship between I_{sc} and T_j is various under different T_c, I_{sc} can be expressed as:

$$I_{sc} = I_{ds} \cdot f(T_j, T_c), \tag{7}$$

where $f(T_j,T_c)$ is a variable that changes with T_j and T_c. In this paper, $f(T_j,T_c)$ is fitted by a 2-5-5-1 ANN structure with hybrid modeling method, that is, ANN has two inputs (T_j and T_c), five neurons in two hidden layers and one output ($f(T_j,T_c)$). Hence, the final expression of I_{sc} can be rewritten as:

$$I_{sc} = \begin{cases} I_{ds\,ANN} & T_j = T_c \\ I_{ds\,ANN} \cdot f(T_j, T_c)_{ANN} & T_j > T_c. \end{cases} \tag{8}$$

According to Eq. (8), I_{sc} has no influence on the channel current I_{ds} under normal working conditions.

4 Verification and discussions

4.1 Verification of the normal working model

The internal gate resistor R_g is set as 4.6 Ω and the gate-source capacitance C_{gs} is set at 1,082 pF, both of which are in accordance with the datasheet [18]. Figures 7 and 8 present the modeling results of output and transfer characteristics, as well as output conductance g_d and transfer conductance g_m. From Figs. 7 and 8, it can be clearly found that not only the I-V characteristics are in good agreement with the datasheet, but

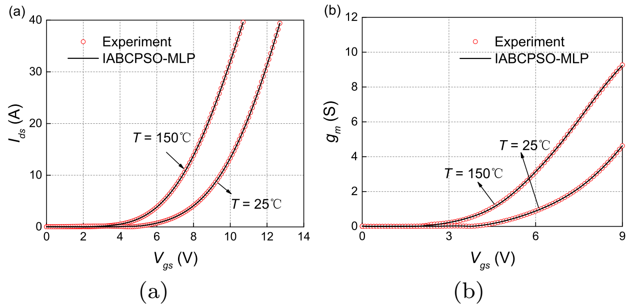

Fig. 8 The comparison results of transfer characteristics and transfer conductance between IABCPSO-MLP and datasheet under different tenperatures. **a** Transfer characterisitics. **b** Transfer conductance g_m

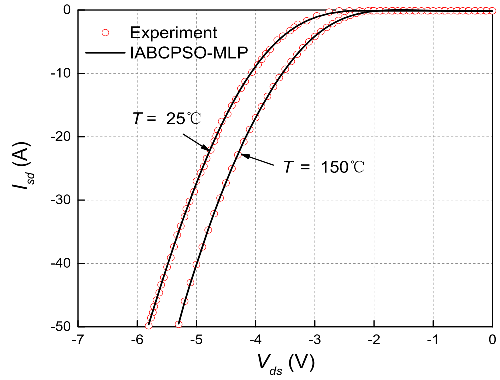

Fig. 9 The comparison results of the current of body diode between IABCPSO-MLP and datasheet under different temperatures

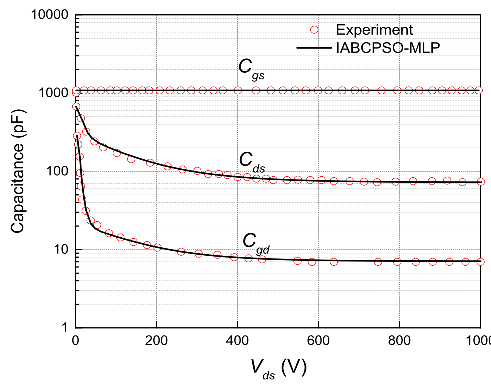

Fig. 10 The comparison results of the internal capacitors between IABCPSO-MLP and datasheet

the small signal parameters that are not exposed in the training process also fit well with the measured data. The accuracy of g_m and g_d has a significant impact on circuit simulation, and the precision of the simulation results of g_m and g_d in this paper further proves the effectiveness of the hybrid modeling method. The comparisons of the modeling of I_{sd}, C_{gs}, C_{ds} and C_{gd} with datasheet are shown in Figs. 9-10, respectively. They are also in good agreement with datasheet. Thus, the

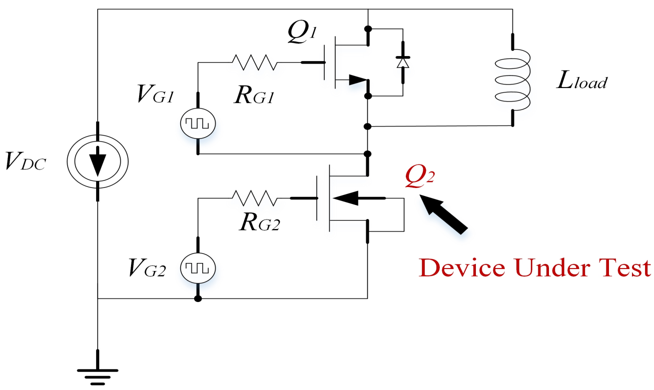

Fig. 11 The diagram of the test circuit

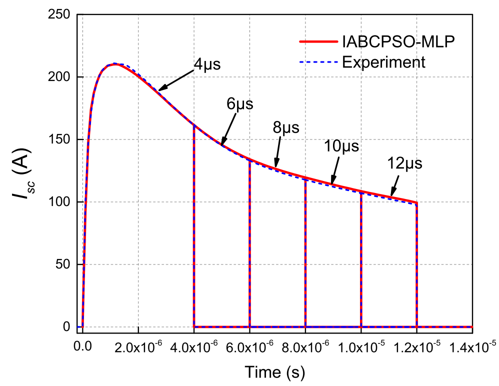

Fig. 12 The comparison results of the simulation current between our proposed short-circuit model and experimental data [20] under different short-circuit times

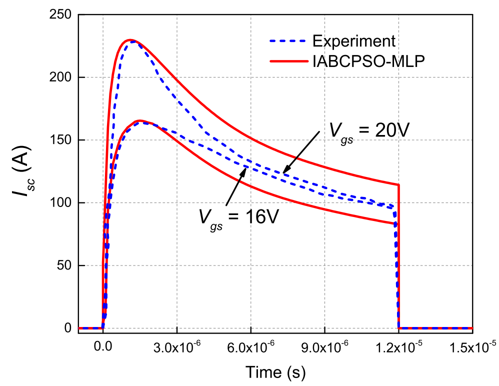

Fig. 13 The comparison results of the simulation current between our proposed short-circuit model and experimental data [20] under different gate-source voltages

accuracy of normal working ANN model has been verified.

From these results, it can be concluded that our proposed hybrid modeling method can accurately predict the non-linear behavior of SiC MOSFETs as well as their temperature effects.

4.2 Verification of the short-circuit model

In order to verify the proposed SiC MOSFET short-circuit model, the simulation results of the proposed short-circuit model are compared with the experimental results in [20] under different conditions. The short-circuit model is implemented in the circuit simulator in the form of Verilog-A, and is put into the test circuit [9] for simulation, as shown in Fig. 11.

Firstly, I_{sc} of different short-circuit times (t_{short} = 4μs, 6μs, 8μs, 10μs and 12μs) under T_c=25℃ of our proposed short-circuit model are compared with the experimental data [20], and the results are shown in Fig. 12. It can be found that the simulation results of short-circuit currents under different short-circuit times agree well with the experimental results [20]. The short-circuit current peak values corresponding to different short-circuit times are the same, which is accurately described by our proposed model.

In addition, I_{sc} of different gate-source voltages (V_{gs} =20V and V_{gs} =16V) under T_c=25℃ are compared with experimental data [20] to verify the validity of the short-circuit model under different circuit parameters. The short-circuit time is set to 12μs, and the comparison results are shown in Fig. 13. The trend of simulation results of I_{sc} under different gate-source voltages is consistent with the experimental data [20]. Although there is a discrepancy in the simulation results of the proposed model, the prediction of the peak values is relatively accurate.

Furthermore, I_{sc} under different case temperatures (T_c =27℃, 67℃ and 128℃) are compared with experimental data [20]. The short-circuit time is set to 10μs, and the comparison results are shown in Fig. 14. The simulation results of I_{sc} under different case temperatures are in good agreement with the experimental results [20]. According to the waveform of I_{sc}, with the increase of the case temperatures, the rising speed of I_{sc} is almost unchanged, the time to reach the peak value of I_{sc} is earlier, and the peak value of I_{sc} decreases. From Fig. 14, it can be found that our proposed short-circuit model can accurately predict the effect of the case temperatures on the short-circuit current, which further verifies the accuracy of the short-circuit model of SiC MOSFETs proposed in this paper.

5 Conclusion

A short-circuit model based on IABCPSO-MLP modeling method for SiC MOSFETs is presented in this paper. In order to overcome the sensitivity of the basic algorithm (LM) of ANN to the initial values and enhance

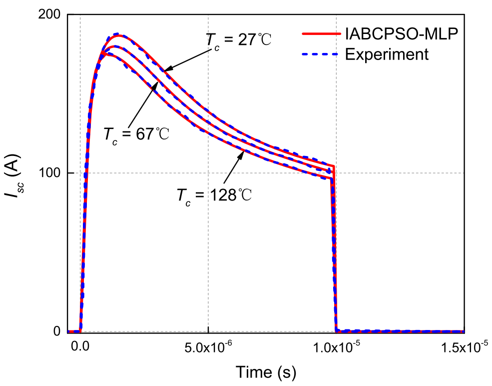

Fig. 14 The comparison results of the simulation current between our proposed short-circuit model and experimental data [20] under different case temperatures

model accuracy, a scheme that uses IABCPSO to find the initial values for ANN is proposed and verified. The model under normal working conditions is verified by comparing the simulation results of the I-V characteristics, C-V characteristics and small signal parameters (g_d and g_m) that are not exposed in the training process with experimental data. And the short-circuit characteristics of the proposed model are proved by comparing short-circuit current waveforms predicted by our model and experimental data under different working conditions. Hence, our proposed SiC MOSFET short-circuit model can facilitate analysis of short-circuit faults and provide guidance for circuit design.

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Declarations

Conflict of Interest Not applicable.
Ethical approval Not applicable.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Both Wanling Deng and Yuan Liu are the corresponding authors of this paper.

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