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Research on Short-Circuit Failure Characteristics of SiC MOSFETs

Yifan Guan[1,a,*]

[1]Nanjing Tianjiabing Senior High School, No. 8 Changjiang New Village, Gulou District, Nanjing, China
a. 161562923@qq.com
**corresponding author*

Abstract: SiC MOSFETs face short-circuit issues in practical applications. When a short circuit occurs in a SiC MOSFET, the high current density causes rapid heat generation, leading to a short short-circuit withstand time. This, in turn, increases the risk of device damage or even the burnout of the entire electrical equipment. To ensure the safe and reliable operation of SiC MOSFETs in electrical systems, research on their fundamental characteristics, short-circuit behavior, and protective driving mechanisms is crucial. This paper investigates two short-circuit failure modes and the factors influencing them.

Keywords: SiC MOSFET, Short-circuit Failure, Influencing Factors.

1. Introduction

With the rapid progress of human society, the environmental pollution problems caused by fossil fuels such as oil, coal, and natural gas have gradually attracted significant attention [1-3]. Unlike fossil fuels, electricity is a clean and environmentally friendly energy source that is easy to store, transport, and convert, making it a focal point for various countries. In the context of the global green revolution, the utilization of new energy sources such as photovoltaic, wind, and hydrogen energy is gradually transitioning from theory to practice. The replacement of non-renewable energy with renewable energy is becoming an inevitable trend. The transmission and conversion of electrical energy are inseparable from the technical support provided by power semiconductor devices. As a third-generation power semiconductor device, SiC MOSFETs, with their characteristics of high temperature and voltage resistance, radiation resistance, low turn-on loss, high operating frequency, and high current density [5-7], have begun to be widely used in the field of new energy.

Although SiC MOSFETs offer significant advantages in material performance compared to traditional Si devices, they still have deficiencies in short-circuit protection [8-10]. Despite their superior voltage resistance, radiation resistance, and heat dissipation, the internal die area of SiC MOSFETs is much smaller than that of traditional Si devices. This smaller die area causes SiC MOSFETs to bear higher short-circuit currents and generate more heat per unit area when a short-circuit fault occurs. If short-circuit protection is not timely, the SiC MOSFET may burn out. Designing a protection detection circuit suitable for SiC MOSFETs is currently a hot topic of research.

In light of the above issues, this paper studies the two short-circuit failure modes and the factors influencing short-circuit failure in SiC MOSFETs.

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2. Short-Circuit Failure Modes

2.1. Hard Switching Short Circuit

A hard switching short circuit refers to the scenario where the main circuit load is already short-circuited before the SiC MOSFET is turned on. When the gate-source voltage of the SiC MOSFET reaches the device's threshold voltage, the MOSFET begins to conduct. Since the main circuit load is already short-circuited before conduction, the drain current flowing through the SiC MOSFET increases sharply. In the power loop of the main circuit, the presence of parasitic inductance causes the rapid rise in drain current to generate an induced voltage across the inductance. Due to the inductor's characteristic of opposing changes in current, the polarity of the induced voltage is opposite to that of the bus voltage, leading to a decrease in the drain-source voltage of the SiC MOSFET.

As the short-circuit current rapidly increases, significant losses occur in the SiC MOSFET, generating more heat and causing the junction temperature to rise, which in turn increases the on-resistance of the MOSFET. This increase in on-resistance hinders the further rise of the short-circuit current, slowing down the current's increase, and the drain-source voltage begins to rise. At this stage, due to the positive temperature coefficient of the channel carrier mobility in the SiC MOSFET, the short-circuit current continues to rise. As the short-circuit duration extends, the operating temperature of the SiC MOSFET rises, and the internal on-resistance continues to increase. With the drain-source voltage remaining constant, the drain current through the SiC MOSFET gradually decreases, eventually decreasing from its peak value, as illustrated in Figure 1.

As the short-circuit state persists, the operating temperature of the SiC MOSFET continues to rise. At time t3, the high temperature causes valence electrons inside the SiC MOSFET to break free, increasing the rate of thermal ionization. At this point, thermal ionization overcomes the reduction in channel carriers, leading to a further increase in drain current, with a positive rate of change. At time t4, the SiC MOSFET is turned off, and the drain current gradually decreases to zero, with the voltage across the device returning to the DC bus voltage.

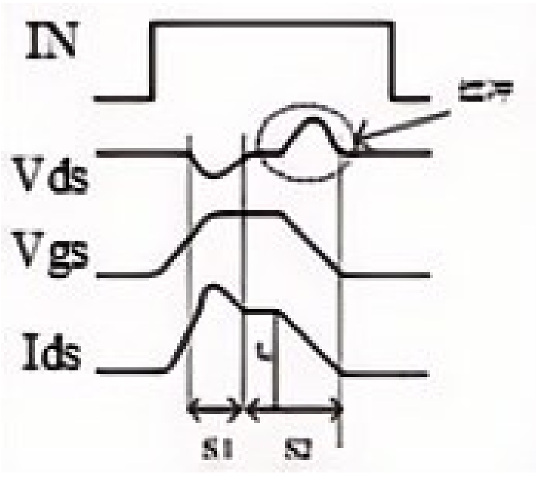

Figure 1: Hard Switching Fault [11]

2.2. Load Short Circuit

Load short circuit refers to the situation where the main circuit load suddenly short-circuits when the SiC MOSFET is in the on state.

A load short circuit refers to the scenario where the main circuit load suddenly short-circuits while the SiC MOSFET is in the on-state. Before time t_1, the SiC MOSFET is conducting normally, with

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both the drain current and drain-source voltage relatively low. At time t_1, the load suddenly short-circuits, causing a sharp increase in drain current. The SiC MOSFET's operating range quickly shifts from the adjustable resistance region to the saturation region, and the gate-source voltage rapidly rises to the DC bus voltage. The rapid increase in gate-source voltage generates a displacement current across the gate-drain capacitance, further raising the gate-source voltage. At this stage, the gate-source voltage slightly exceeds the normal driving voltage. As observed in the static transfer characteristics of the SiC MOSFET, the increase in gate-source voltage expands the rising potential of the drain current. When the drain current reaches its peak at time t_2, the gate-source voltage quickly discharges through the gate-source capacitance, dropping to the normal driving voltage.

At this stage, similar to the hard switching fault, the substantial short-circuit current causes significant losses in the SiC MOSFET, generating a large amount of heat and causing the junction temperature to rise. The internal on-resistance of the SiC MOSFET continues to increase. With the drain-source voltage remaining constant, the drain current gradually decreases from its peak value, as shown in Figure 2.

As in the hard switching fault, the short-circuit state persists, causing the junction temperature of the SiC MOSFET to continue rising. At time t_3, the high temperature causes valence electrons to break free, increasing the rate of thermal ionization. Thermal ionization then overcomes the reduction in channel carriers, leading to a further increase in drain current, with a positive rate of change.

Finally, the SiC MOSFET is turned off, and the drain current gradually decreases to zero, with the voltage across the device returning to the DC bus voltage.

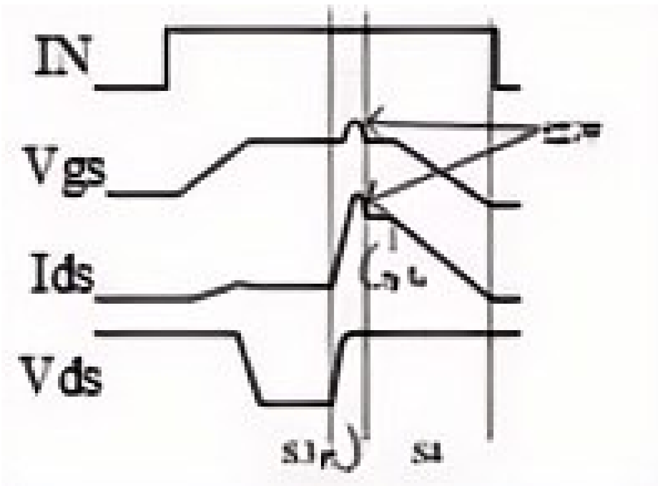

Figure 2: Load Short Circuit [11]

3. Influencing Factors of Short-Circuit Failure

3.1. Gate-Source Capacitance

To analyze the influence of the gate-source capacitance of the SiC MOSFET on a hard switching short circuit, the gate-source capacitance was set to 10 pF, 100 pF, 200 pF, and 300 pF, respectively, while keeping other circuit parameters constant (DC bus voltage: 600 V, driving voltage: +20/-5 V, driving resistance: 20 Ω). The waveform changes of the drain current and drain-source voltage of the SiC MOSFET under different gate-source capacitance values were compared and observed. Figure 3(a) & figure 3(b) shows the simulation waveform diagram of the hard switching short circuit in the SiC MOSFET under different gate-source capacitances. It can be observed that the gate-source capacitance has little influence on the rising speed of the short-circuit current and the turn-off voltage, as shown in Figure 3.

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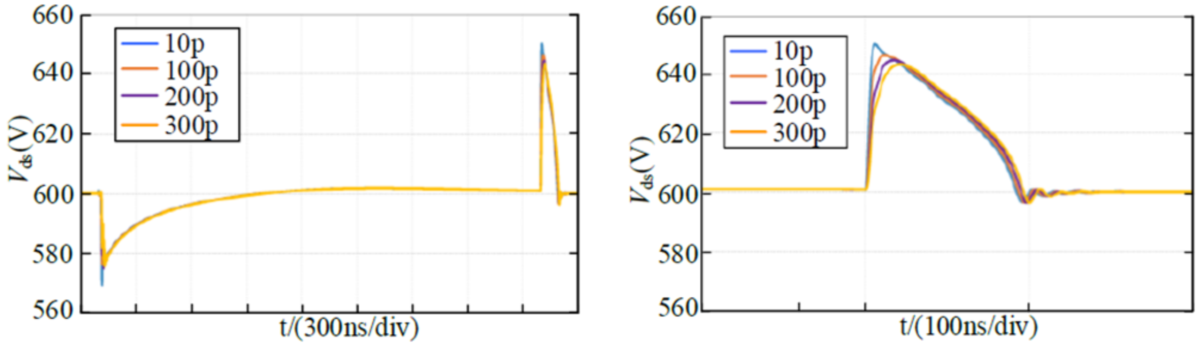


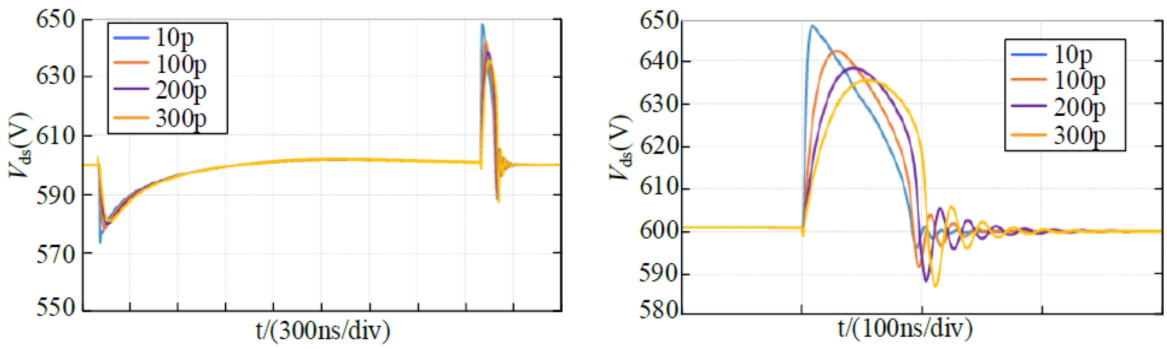
(a) (b)

Figure 3: Simulation diagram of hard switch short-circuit Vds under different C_{gs} [4]

3.2. Gate-Drain Capacitance

To analyze the influence of the gate-drain capacitance of the SiC MOSFET on a hard switching short circuit, the capacitance was set to 10 pF, 100 pF, 200 pF, and 300 pF, respectively, while keeping other circuit parameters constant. The changes in the switching waveforms of the SiC MOSFET under different gate-drain capacitance values were then compared, as shown in Figure 4(a) & figure 4(b).

As the gate-drain capacitance gradually increases, the rising speed of the short-circuit current in the SiC MOSFET gradually slows down, but the peak value of the short-circuit current remains almost unchanged. The size of the gate-drain capacitance primarily affects the rising speed of the short-circuit current. In terms of the turn-off voltage, the smaller the gate-drain capacitance, the higher the turn-off voltage. Compared to the short-circuit current, the gate-drain capacitance has a more pronounced effect on the turn-off voltage. In practical engineering applications, the rising rate of the short-circuit current can be appropriately adjusted by varying the gate-drain capacitance.



(a) (b)

Figure 4: Simulation diagram of hard switch short-circuit Vds under different C_{gd} [4]

3.3. Line Stray Inductance

To analyze the influence of stray inductance in the line on a hard switching short circuit in the SiC MOSFET, the inductance was set to 10 nH, 20 nH, and 30 nH, respectively, while keeping other circuit parameters constant (DC bus voltage: 600 V, driving voltage: +20/-5 V, driving resistance: 20 Ω). The waveform changes of the drain current and drain-source voltage of the SiC MOSFET under different stray inductance conditions were compared and observed.

As the stray inductance in the line increases, the rising speed of the short-circuit current in the SiC MOSFET slows down, though the reduction in speed is minimal and can almost be ignored. The time

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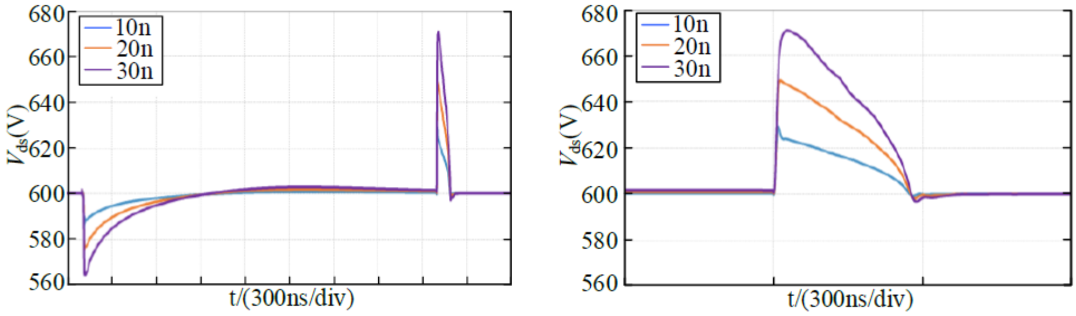
required for the short-circuit current to reach its peak value also increases, but the peak value itself remains almost unaffected. The peak value of the short-circuit current is essentially the same, as shown in Figure 5(a) & figure 5(b).

When a short circuit occurs in the circuit, the sudden increase in current generates a large induced voltage on the stray inductance of the line, which significantly impacts the drain-source voltage of the SiC MOSFET. During the turn-off process, a larger stray inductance in the line results in a higher induced voltage in the inductor. When superimposed with the bus voltage, the peak drain-source voltage when the SiC MOSFET is turned off becomes larger. This excessive drain-source voltage can cause breakdown of the SiC MOSFET, leading to damage or even failure of the switching device.



(a) (b)

Figure 5: Simulation diagram of hard switch short-circuit Vds under different L_S [4]

4. Conclusion

As a third-generation power semiconductor device, the SiC MOSFET, with its characteristics of high temperature and voltage resistance, radiation resistance, low turn-on loss, high operating frequency, and high current density, has begun to be widely used in the field of new energy. This paper has examined the working principles of SiC MOSFETs through the analysis of two short-circuit failure modes and their influencing factors. The two short-circuit scenarios for SiC MOSFETs were introduced, and the causes of these short circuits were explained in detail. The output characteristics of the device under the conditions of hard switching short circuit and load short circuit were analyzed. Furthermore, the influence of various parameters in the driving circuit and the main circuit on the short-circuit behavior of the SiC MOSFET was studied. These studies provide a theoretical foundation for the protection and safe operation of SiC MOSFETs.

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