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Analysis of short-circuit behavior and failure modes in SiC power devices

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Abstract. This essay presents the advantages of SiC power devices, while the short-circuit characteristics limit their development. The device short-circuit will seriously affect the efficiency of the use of the period. When a load short circuit occurs, both ends of the power MOSFET device will be directly connected to the high bus voltage; therefore, the short circuit process poses a great challenge to the device's ability to withstand high voltage, high current, and high junction temperature simultaneously. In this thesis, the short-circuit process of SiC power devices is investigated by designing a detection circuit, and two failure mechanisms of SiC MOSFET power devices are explained through the understanding of the failure mechanism.

Keywords: SiC power devices, short-circuit characteristics, failure mechanism, MOSFET.

1. Introduction

SiC MOSFETs are a rapidly developing type of SiC device. They offer superior physical properties such as higher thermal conductivity, lower conduction loss, and higher breakdown voltage compared to silicon devices [1]. These properties make SiC MOSFETs promising for high temperature, high voltage, and high frequency applications. However, it's important to note that SiC MOSFETs also have short-circuit reliability concerns [2]. In contrast to IGBTs, which possess a short-circuit current rating of approximately 4-6 times their designated current, SiC MOSFETs are capable of surpassing 10 times their rated current during short-circuit events [3]. Additionally, due to the smaller size of SiC MOSFET chips compared to IGBTs, there is potential for an increased short-circuit current [4]. SiC MOSFETs have a higher short-circuit current density than IGBTs, which means that they have a shorter short-circuit withstand time [5].

Silicon carbide power semiconductors have gained attention due to their advantageous properties, such as reduced switching losses, high power density, and enhanced temperature tolerance [6]. The aforementioned properties enable the development of more efficient and compact system solutions. Silicon carbide power devices (SiCs) exhibit superior electrical characteristics compared to traditional silicon (SI) power devices, which can greatly enhance the performance of power electronic converters [7]. With the increasing maturity of SiC process technology, SiC power devices are expected to replace traditional SI power devices and gain wider application and development in future power electronics converters [8]. Currently, as a new type of wide-band semiconductor power device, the SiC MOSFET is the most commercialized SiC power device, which faces more serious short-circuit problems due to

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higher current densities, smaller chip sizes, and shorter short-circuit withstand times [9]. SiC power devices have a higher withstand voltage level, a higher switching frequency, lower switching losses, and can withstand higher operating temperatures; they will be expected to replace conventional SI power devices [10]. However, although SiC MOSFETs have shown promise in terms of reliability, there is still a need for thorough testing under extreme operating conditions like short circuits. Therefore, this research investigates the short-circuit characteristics of SiC power devices [11].

In this section, the short-circuit properties of SiC power devices are explored. The first part discusses the principles and design of short-circuit circuits, while the second part examines the overall short-circuit process of SiC power devices. Finally, the third part explores the two main failure modes of power devices and proposed solutions to mitigate these failures.

2. Short circuit principle

SiC MOSFETs have the advantages of fast switching speed, high voltage withstands, low on-resistance, and a high operating temperature. At the same time, the constraints imposed by a variety of factors make us consider the reliability and stability of the power device. In this paper, we will focus on how power devices are affected by the causes of short circuits and study the process of a short circuit and how it affects the reliability of power devices [12].

Nowadays, the short-circuit problem of SiC power devices has seriously affected the widespread use of power devices. Because a single short-circuit withstand time and repeated short-circuit tests easily lead to device gate degradation, short-circuit withstand capability is weak and has become one of the main factors limiting the widespread use of SiC MOSFET power devices [13].

Power devices can experience two distinct types of short circuits: hard switching faults (HSF, also known as class I short circuits) and faults under load (FUL, also known as class II short circuits) [14]. Hard Switching Fault (HSF) is a power device where the circuit has been shorted before turning on, the device is continuously subjected to bus voltage before and after turning on, and the device current rises to the short circuit current. In the event of a short circuit with load (FUL), a power device's conduction circuit becomes shorted, resulting in a transient rise of the device's voltage to the bus voltage fault state. Meanwhile, the device's current increases from the load current to the level of the short-circuit current [15].

3. Short circuit process

Since the SiC MOSFET power loss is greater and the heating is more serious under hard-switching fault, which is a more severe test for the device, this paper focuses on the primary analysis of hard-switching faults in SiC MOSFETs. Figure 1 presents a detailed overview of the short-circuit behavior of SiC MOSFETs during HSF conditions, comprising four distinctive stages.

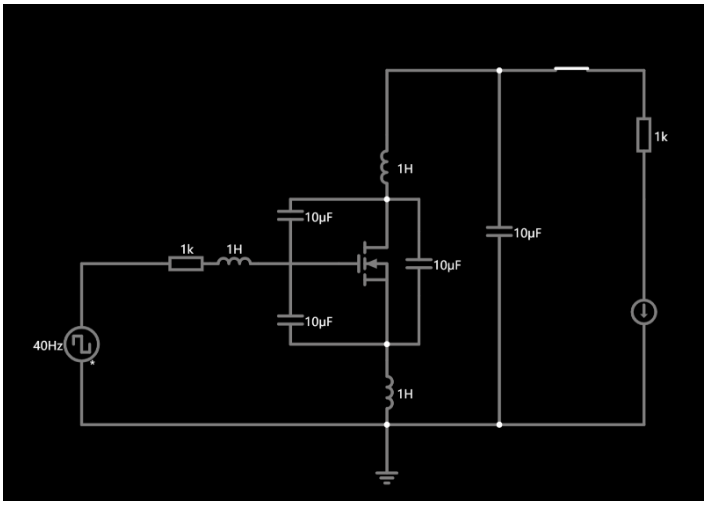

Figure 1. Test circuit schematic [16].

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In the test circuit, a capacitor is connected in parallel with a high-voltage DC power supply. To carry out a short-circuit test, it's necessary to charge a capacitor to a predetermined voltage level, which serves as the energy source. The capacitance of the capacitor used in the test circuit is 10 mF. In the main circuit, to test the device under examination, it's typical to link a high-current level in series with it. The upper IGBT tube serves as a circuit breaker, which disconnects the main circuit when the device under test experiences a short circuit failure. This prevents the device under test from being damaged and facilitates subsequent failure analysis.

The SIC MOSFET is off until t1, then the CB turns off.

First stage of short circuit (t1-t2): After the gate signal appears, the device turns on directly from the linear operating region into the saturated operating region. Due to the presence of parasitic inductance in the main circuit, a reverse voltage is introduced as the drain short-circuit current rises rapidly, which can be expressed by the following equation:

$$U_{Lloop} = L_{loop} \times \frac{di}{dt} \quad (1)\ [18]$$

The initial phase of a short circuit is characterized by a reduction in the drain-source voltage (Uds), caused by the parasitic inductance in the main circuit. Equation (2) outlines the expression for Uds:

$$U_{ds} = U_{DC} - U_{Lloop} \quad (2)\ [18]$$

As Id increases, the power loss of SiC MOSFETs also increases. This leads to an increase in temperature and a rise in on-resistance. During short-circuit operation, the Id keeps increasing because of the rise in channel mobility with temperature. As channel mobility rises with temperature. Therefore, the change in channel resistance at the onset of the short circuit determines the short circuit current, which exhibits a continuous increasing trend.

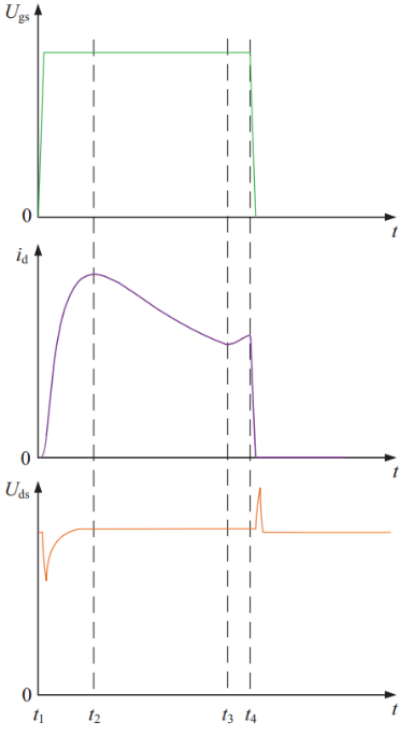

Figure 2. Short-circuit waveforms of SiC MOSFET for hard-switching fault [17].

During the second stage of the short circuit (t2-t3), the MOS channel (and drift region) experience a decrease in carrier mobility due to the rapid rise in semiconductor junction temperature caused by self-heating. This leads to a reduction in drain current at a lower rate than the increase in thermally excited current due to overheating. After the short circuit break, the slope of the short circuit current shifts from positive to negative, following its peak.

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The third stage of the short circuit (t3-t4): As the junction temperature continues to rise, the short circuit current slope changes from negative to positive because the high temperature causes the device's thermal excitation current to increase and the drain current reduction rate is lower than the thermal excitation current increase rate caused by overheating.

Equation 3 can be used to calculate the device's short-circuit critical energy, which represents the maximum short-circuit energy that the device can tolerate within the given short-circuit time.

$$E_C = \int_{t_1}^{t_4} v_{ds} i_d dt \quad (3)\ [18]$$

The fourth stage [t4~]: following a safe and reliable shutdown of the device, there are two potential outcomes. The first is that the leakage current drops to zero, indicating that the device has been safely shut down. The second scenario involves the tail leakage current persisting after the shutdown process, which can lead to thermal runaway and eventual device failure.

4. Device failure mechanisms

SiC MOSFETs can typically fail in one of two ways: through thermal runaway or gate interlayer dielectric failure.

4.1. Thermal runaway failure

When the temperature at the junction surpasses its maximum capacity, this can trigger a rapid escalation in temperature known as thermal runaway, which can cause a source block and result in thermal runaway. After being turned off, SiC MOSFETs may experience thermal runaway in certain situations. After the device is turned off, there is still a high leakage current, which leads to high energy dissipation within the device. The low gate turn-on voltage in this failure mode can be attributed to the significant influence of the gate voltage on the device failure mechanism. As the duration of the short circuit increases, there is a slight and gradual increase in the gate current that persists until the end of the short-circuit pulse [19]. However, unlike the gate source failure mode, the trailing current increases dramatically instead of decreasing after the SiC MOSFET turns off, and the increased leakage current leads to a rapid rise in junction temperature and the formation of positive temperature feedback. Failure Mode II, which is defined as the burnout of SiC MOSFETs resulting from thermal runaway, is one possible outcome.

4.2. Gate source failure

The occurrence of a short-circuit failure in SiC MOSFETs is often linked to a rapid increase in short-circuit saturation current during turn-on. This can cause a significant voltage spike at the gate source due to the presence of parasitic inductance and high di/dt in the source circuit. A SiC MOSFET typically exhibits a substantial trailing current after it is turned off, which ultimately dissipates to zero. During the same period, the gate-source voltage exhibits an abrupt increase from negative to 0V, signifying the emergence of a significant leakage current between the gate and source and resulting in the gate-source short-circuit failure. The gate current and gate voltage of SiC MOSFETs can be employed as key parameters for anticipating gate-source failure. The gate current variation can be calculated by measuring the voltage drop changes across the external gate resistance of the SiC MOSFET [20]. The turn-on and turn-off process is the process of charging or discharging the gate capacitor by the gate drive current. Therefore, there is a large gate current spike. After the device is fully on, the gate current is basically zero, but with the increase in short circuit time, the gate current gradually increases, and because of the larger current flowing through the external gate drive resistor, the gate source voltage decreases. The analysis of the failed device revealed that the gate source was shorted, but the drain source still retained its high voltage blocking capability. This mode of failure is referred to as failure mode I in this study [21].

According to the previous analysis, to prevent gate-source short-circuit failure in SiC MOSFETs, it is important to minimize the thermal-mechanical stress between the gate interlayer dielectric and the source metal material. This is one of the two primary failure modes of SiC MOSFETs. According to

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research, one way to increase the short-circuit capability of SiC MOSFETs is to opt for a source metal material that has a thermal expansion coefficient that closely matches that of the dielectric.

5. Conclusion

This paper explores the device advantages of SiC power devices over SI devices and explains the importance of studying the short-circuit characteristics. The short-circuit characteristic test circuit was utilized to investigate the entire process of short-circuits in power devices. This study provided an explanation of the basic characteristics of short-circuit currents and their formation process, as well as a classical waveform diagram of short-circuit events in power devices. The research also explored the two failure mechanisms of short-circuits and presented a detailed introduction to the two failure modes of SiC power devices. Additionally, the study offered device improvement methods to address thermal runaway failure.

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