The operating life of a wide-bandgap power device over a wide temperature range

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Converter plays a vital role in energy systems, such as high-speed rail traction converters, DC transmission converter valves, wind power converters, electric vehicle (EV) chargers, EV motor drivers and other electrical energy conversion applications.[1] The power devices are a crucial part of the converter system. Compared with traditional silicon devices, the usage of wide-bandgap silicon carbide (SiC) power devices has been developing rapidly in recent years. SiC Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) have higher breakdown field strength, lower on-resistivity and faster switching speed, showing broad application prospects for the future, for instance Mars Exploration[2] and Space Station.[3]

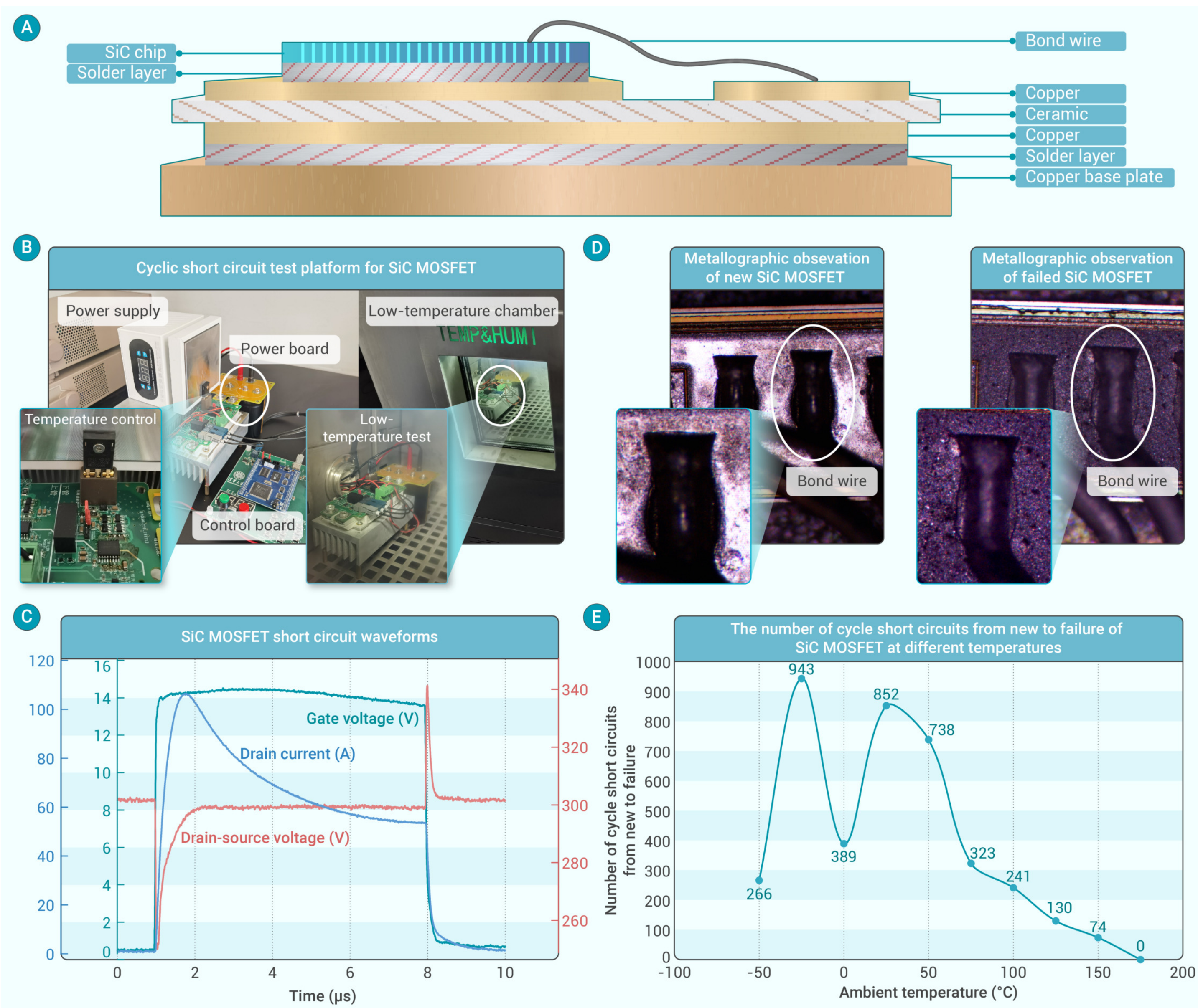

Figure 1. The research of test platform and results of SiC MOSFET life investigation over a wide temperature range (A) The structure of the SiC MOSFET. (B) Cyclic short circuit test platform for SiC MOSFET. (C) SiC MOSFET short circuit waveforms. (D) The comparison of the new SiC MOSFET with the failed SiC MOSFET with metallographic microscope. (E) The number of cycle short circuits from new to failure of SiC MOSFET at different temperatures.

In practical applications, power devices are often subjected to a wide temperature range,[4] such as the high-temperature weather of up to 45℃ on the ground in summer. The power device's ambient temperature can even exceed 100℃ when coupled with limited space inside the converter. In winter, or the North and South Pole, the ambient temperature can easily reach -50℃. In such an environment, how will the life of the SiC MOSFET change? The datasheet generally gives the operating temperature range of silicon carbide devices as -40 to 175℃, but the life outside this temperature range lacks the corresponding data description.

Tsinghua University professor Pinjia Zhang's team has carried out relevant research on this problem. The Planar gate SiC MOSFET is taken as the research object to carry out the relevant life research. The structure of the SiC MOSFET is shown in Figure 1A, including the SiC chip, bond wires and solder layer. The life of power devices is investigated by accelerated aging test.[5] Short circuit often occurs in practical applications. Hence, the short circuit characteristics of the power device is crucial for setting the short circuit protection of the power device. At the same time, the short circuit characteristic of the power device is one of the key indicators of the safe operating area. Therefore, it is necessary to study the short-circuit characteristics of the device. The team built a cyclic short-circuit test platform. The key circuit of the test platform is shown in Figure 1B.

The experimental platform mainly includes the SiC MOSFET under test, high voltage Direct Current (DC) power supply (IT6723G), bus capacitor (2000uF), driver board, control board (based on TMS320F28335) and IGBT module for failure protection. The device under test is Cree's SiC MOSFET C3M0120065D. The short circuit duration of each cycle short circuit is 7μs, the drain-source voltage is 300V, and the time interval of two short circuits is 1s.

The platform can realize any μs-level short-circuit duration control, and the setting of any two adjacent pulse intervals and the number of short-circuit pulses can be set arbitrarily. Once the short-circuit failure of SiC MOSFET is detected, the number of short-circuit cycles performed is automatically recorded. The temperature of SiC MOSFET as the tested object can be flexibly changed. The device under test is heated separately by the heating board above room temperature and refrigerated by a low-temperature chamber below room temperature.

The short-circuit waveform of the SiC power device is tested, as shown in Figure 1C. When the device is short-circuited instantaneously, the current of the device rises rapidly, and then the junction temperature also rises rapidly corresponding. As the junction temperature increases, the on-state resistance of the SiC MOSFET rises, leading to a decrease in the short-circuit current of the device. In the short-circuit process of the SiC MOSFET, the voltage and current are relatively large, and the power loss reaches more than 30kW, which can be sustained in a short time (several μs). The instantaneous short circuit energy will be converted into heat, which causes the temperatures of the device channel and Junction Field-Effect Transistor (JFET) region to rise sharply, and changes such as electron injection occur. At the same time, the severe temperature rise will also cause the aluminum on the surface of the device to melt. When the single short-circuit energy of the device exceeds the maximum tolerable energy of the device, the device fails. On the other hand, when the damage of the device accumulates to a certain extent, the device will also fail. Therefore, the higher the ambient temperature, the smaller the maximum tolerable energy of the device, and the damage of a single short circuit to the device is also more serious. At the same time, due to the difference in thermal expansion coefficient between the bond wire and the chip, the welding is subjected to huge shear stress at the moment of short circuit, which might destroy the adhesion of the bond wire root.

During the test, it was found that the cyclic short circuit of the device is a cumulative aging process. That is, the life of the device reduces with the increase of short circuit cycles. Besides, no matter how long the interval occurs (generally more than seconds after the device's last short circuit reaches thermal stability), the number of short circuits the device can withstand is constant. Life assessment based on cyclic short circuits has significant reliability.

The SiC MOSFET is cyclically short-circuited until the failure occurs. The new SiC MOSFET and the failure SiC MOSFET are compared and observed under a metallographic microscope, as shown in Figure 1D. There might be cracks in the root of the bond wire. Therefore, after the circuit short circuit of the SiC MOSFET, the bond wire might have degradations (heel-crack or lift-off). Furthermore, analysis of the electrical parameters revealed aging in the gate oxide layer of the SiC MOSFET.

The short-circuit aging of SiC MOSFET at different ambient temperatures (-50-175℃) is further tested, and the test results are shown in Figure 1E. It can be analyzed from the results that the operating life of wide-bandgap SiC MOSFET is closely related to the ambient temperature. At temperatures below 25℃, there is no obvious monotonic relationship between the life of the device and the temperature. At -50℃, lower than the recommended temperature limit, the device still has a maximum life of about 28%. At temperatures higher than 25℃, the higher the ambient temperature is, the shorter the life is. At more than 100℃, with each increase of 25℃, the device life is reduced by half. The device cannot withstand the short circuit test in our setup when the ambient temperature is 175℃.

The relevant research has important reference significance for the future application of SiC power devices, system design and life evaluation under different environmental conditions.

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DECLARATION OF INTERESTS

The authors declare no competing interests.