Silicon Carbide Material and Railway Electrical traction Innovation

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Abstract. With the development of new materials and new energy industries, power devices have also made great progress. Compared with traditional silicon-based power electronic devices, wide-band gap semiconductor devices based on silicon carbide which are considered to be an important alternative to silicon-based devices, have excellent properties such as high breakdown voltage, thermal conductivity, and electron saturation drift and radiation resistance. At the same time, power electronic devices are widely used in high-speed railway. The application of a new type of silicon carbide power device in electrical traction is discussed. The experiment of system characteristics shows that the power device made of silicon carbide can effectively reduce the power loss of the system, adapt to the bad working conditions, and make the equipment lightweight.

1. Introduction
Compared with the traditional silicon-based power electronic devices, the third generation semiconductor power devices based on SiC material is gradually emerging in the fields of new industry, new energy, smart grid, new generation mobile communication, rail transit and national defense with its higher breakdown voltage, thermal conductivity, electron saturation drift and radiation resistance [1]. There are two important research directions in this field: (1) basic research on epitaxial growth of key materials (silicon carbide); (2) basic research on device performance optimization and innovative application [2].

High-speed railway systems have long been popular because of their fast transportation speed, high stability, and low overall cost. With the continuous development of the application of electrical traction technology [3], the performance index and reliability requirements of power electronic devices are becoming more and more stringent. Power electronic devices are required to have higher current density, higher operating temperature, stronger heat dissipation capacity, higher operating voltage, lower conduction voltage drop and faster switching time [4].

The switching performance of silicon-based power devices is close to its theoretical limit determined by material properties, and the potential to continue to improve the performance of electric traction systems with silicon-based power devices is limited [5]. Based on the analysis of the performance advantages of silicon carbide power devices, the application of power devices based on silicon carbide materials in electrical traction is explored. The experiments of system characteristics show that the power device made of silicon carbide can effectively reduce the power loss of the system, adapt to the bad working conditions, and make the equipment lightweight.
2. Power device characteristics based on silicon carbide

2.1. Silicon carbide material

In recent years, as a new type of wide band gap semiconductor material, silicon carbide has attracted more and more attention from the industry due to its excellent physical and electrical properties. Compared with silicon materials, silicon carbide materials have many important characteristics: higher breakdown electric field strength 2~4MV/cm; maximum junction temperatures of up to 600° and so on. Therefore, even in a drift layer thinner than Si or GaAs (about 1/10 of them), silicon carbide can also withstand higher voltages and thus have lower on-resistance. Silicon carbide Schottky barrier diodes are close to the limits of 4H-SiC unipolar devices and have withstand voltages up to 600V. These products are currently being commercialized by companies such as Infineon and Cree. Silicon carbide Schottky barrier diode can effectively avoid the problem of reverse recovery and reduce the switching power loss of the diode, so that the device can be used in circuits with high switching frequency. The development of silicon carbide semiconductor materials and power devices is shown in figure 1.

![Figure 1. Development of SiC semiconductor materials and power devices](image)

2.2. Performance comparison

At present, the development of power devices based on silicon carbide materials has been relatively mature. Table 1 gives a comparison of the characteristic parameters of some second-generation semiconductor materials and third-generation silicon carbide semiconductor materials.

As can be seen from Table 1, the material properties of silicon carbide have the following main advantages:

a) The critical breakdown electric field is ten times higher than that of silicon, which greatly increases the current density and withstand voltage capacity of the semiconductor power device, and also greatly reduces the conduction loss.

b) The band gap is about three times wider than that of silicon, which greatly reduces the leakage current of the semiconductor device and makes the semiconductor device radiation resistant; In addition, due to the high temperature resistance of silicon carbide materials, it has advantages in high temperature applications. The working temperature can reach 6000° in theory.

c) The thermal conductivity is three times that of silicon, and it has excellent heat dissipation performance, which can greatly improve the integration and power density of silicon carbide.
(d) The electron saturation drift velocity is twice as fast as that of silicon, which allow the semiconductor device to operate at higher frequencies.

Table 1. Comparison of characteristic parameters of typical semiconductor materials

| Materials          | Si  | GaAs | 4H-SiC |
|--------------------|-----|------|--------|
| Energy bandwidth (eV) | 1.12| 1.43 | 3.03   |
| Relative dielectric constant | 11.9| 13.1 | 10.10  |
| Critical breakdown field strength (mV/cm) | 0.3 | 0.4  | 2.20   |
| Electronic saturation drift speed (10^7 cm/s) | 1.00| 1.00 | 2.00   |
| Electron mobility (cm²/Vs) | 1500| 8500 | 1000   |
| Thermal conductivity (W/cm·K) | 1.5 | 0.46 | 4.9    |

Therefore, the semiconductor material silicon carbide has the advantage that silicon material cannot reach, so the power device made of this semiconductor material can withstand higher voltage, output higher energy density and adapt to higher working environment temperature. In theory, it can meet the requirements of the current electrical traction technology for power electronic devices with higher current density, higher operating temperature, stronger heat dissipation capacity, higher operating voltage, lower conduction voltage drop and faster switching time.

2.3. Price forecast

Fig. 2 is a market price forecast for a variety of new power electronic devices based on silicon carbide materials. It can be seen that with the progress and development of technology, the price of power devices based on silicon carbide material will be gradually reduced, which promotes its commercial application process.

![Figure 2. Price trend of Power Devices](image-url)
3. Application Analysis in Electrical Traction

3.1. Construction of Experimental platform
When the locomotive is in traction condition, the pantograph transmits the 25kV single-phase power frequency alternating current of the catenary to the traction transformer through the pantograph and the high-voltage electrical apparatus, and the traction transformer step-down output single-phase AC electricity is supplied to the traction converter \[4\]. Then the traction converter which realize the conversion from electric energy to mechanical energy realizes the AC-DC-AC conversion of electric energy through a single-phase rectifier power module, a middle link and a three-phase inverter power module, and outputs three-phase AC electricity with adjustable voltage and frequency to drive traction motor \[5\]. Aiming at the application of AC transmission system with 1700V voltage level power device, the traditional silicon-based power device is partly and completely replaced by silicon carbide power device, and the experimental study on the system characteristics is carried out. The experimental circuit diagram is shown in figure 3.

![Experimental circuit diagram](image)

**Figure 3.** Experimental circuit diagram

3.2. Application contrast analysis
Fig. 4 shows the performance comparison results of a 1700V voltage level converter in the case of silicon carbide power devices replacing some traditional silicon-based IGBT power devices. As can be seen from fig. 4, the installation area of the converter has not changed since only the continuation diode uses a silicon carbide power device. However, because the silicon carbide power device works in a unipolar state, the reverse recovery charge is basically zero. Therefore, the self-transient loss caused by reverse recovery is reduced by 98%, and the total switching loss of power devices is reduced by 84.1%.
Fig. 5 shows the performance comparison results of a 1700V voltage level converter in the case of silicon carbide power devices replacing all traditional silicon-based IGBT power devices. As can be seen from fig. 5, the installation area of the traction converter is reduced by 23%; the silicon carbide power device operates in a unipolar state, the reverse recovery charge is basically zero. Therefore, the self-transient loss caused by reverse recovery is reduced by 98%, and the total switching loss of power devices is reduced by 84.1%.

It can be clearly seen from the comparison results of the above experiments that the switching loss of the silicon carbide power device is greatly reduced. The reduced heat generation of the power module
will reduce the requirements of the device for the power module heat sink and the requirements of the entire converter cooling system, resulting in a reduction in system volume and weight. Power devices can be switched at higher frequencies, which will reduce the volume and weight of passive components such as transformers, capacitors, reactors and so on. The improvement of the overall volume and weight of the converter will be beneficial to the weight management and equipment arrangement of the vehicle, and improve the overall performance of the vehicle.

4. Conclusion
Wide band gap power devices based on silicon carbide represent the development direction of power devices. With the development of electric traction technology in high-speed railway, new requirements have been put forward for power devices in the aspects of large capacity, high power density and integration. The IGBT power devices based on silicon-based materials are restricted by their physical characteristics which is difficult to meet the current application needs. Based on the above experimental study of system characteristics, silicon carbide power devices have significant advantages in withstand voltage grade, operating temperature, switching loss and so on, which can meet the development needs of electrical traction technology. With the further maturity of related technologies, it will lead the electric traction technology of high-speed railway in China into the era of high efficiency, high reliability and low cost.

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