Current Situation and Development Prospect of Silicon Carbide Power Electronic Devices in Modern Power System

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Abstract

With the development of society and social progress, semiconductor devices in the production and production process have been developed to a certain extent. Silicon carbide is a kind of broadband material. Its main characteristics are high thermal conductivity, high saturated electron drift rate and high breakdown field strength. Through this new type of semiconductor, high power, high voltage and high temperature applications can be realized. In addition, silicon carbide has been widely used in power systems due to its cost reduction and performance improvement. In this paper, the performance and application of silicon carbide power electronic devices in electronic systems are analyzed and discussed in depth, and the future development of silicon carbide power electronic devices is prospected reasonably.

Keywords

Silicon carbide; power devices; power system.

1. Introduction

For more than half a century, the rapid development of power electronics technology based on silicon-based power electronics devices has played a decisive role in science, technology, economy, military and other aspects of the world. Today, power electronics technology covers the vast majority of key areas related to national economic development and long-term national security, such as materials, manufacturing, information and communication, aviation and transportation, energy and environment. Power electronics technology has become one of the key basic technologies in social development and national economic construction. At present, power electronics technology has gradually become the key technology to implement the transmission, processing, storage and control of electric energy in power system, to ensure the safe, reliable, efficient and economic operation of electric energy. At the same time, it is also the key factor to realize the optimal utilization of electric energy and greatly improve production efficiency and energy utilization efficiency. Especially since the 1990s, the introduction of renewable energy, represented by wind power, has greatly promoted the development and progress of modern power system technology. With the development of high-voltage and high-power power power electronic devices in recent years, the improvement of modularization, modularization and intellectualization of converters, and the improvement of the performance of control strategies and modulation strategies, power electronic devices will play a greater role in modern power systems. However, due to the limitations of silicon-based power electronic devices in high voltage and high power levels, the main circuit topology of these power electronic devices has to adopt device series-parallel technology and complex topology structure to meet the corresponding practical application requirements. This will lead to the reduction of device reliability, the increase of cost and loss, which will seriously restrict the development of power electronics technology in modern power system. Therefore, in order to improve the performance of power semiconductor devices, power electronic devices using new device structures and wide bandgap semiconductor materials are the current development trend.

Silicon carbide, as a wide band gap semiconductor material, has attracted much attention in recent years. Its excellent physical and electrical properties, such as wide band gap, high critical breakdown electric field, high thermal conductivity and high electron saturation drift speed, make it break through the performance limits of traditional silicon-based devices in terms of voltage resistance, operating frequency and conversion efficiency, thus reducing power consumption by more than 30%. Therefore, we must fully understand and understand the current development status, design ideas, manufacturing technology and its application in smart grid of ultra-high voltage SiC power and electronic devices at home and abroad, invest human and material resources to accelerate development and make every effort to catch up with and surpass them.

2. A Brief Introduction to the Development of SiC Power Electronics Devices

2.1 Characteristics of SiC Power Devices

Table 1 Important Electrical Properties of Various SiC Crystal Forms

Material parameters/300K	3C-SiC	4H-SiC	6H-SiC
Bandwidth/eV	2.2	3.23	3
Saturated electron drift velocity(km/s)	270	200	200
Thermal conductivity(W/cm·K)	4.9	4.9	4.9
Breakdown field(MV/cm)	0.8	1	3
Dielectric constant	9.72	9.66	9.76

Because of these characteristics, SiC power devices are the preferred "successors" of silicon-based power devices in the field of power electronics. They are especially suitable for the requirements of power electronics technology for high power, high voltage, high frequency and high temperature, anti-irradiation and other working conditions. Because of the low conduction loss and switching loss of SiC power devices, it is also known as a "green energy" power device in the field of semiconductor devices. So far, great breakthroughs have been made in the research of SiC power devices. SiC Schottky diode (SBD), SiC metal oxide field effect transistor (MOSFET) and SiC insulated gate bipolar crystal (IGBT) have been developed successively.SiC gate can turn off thyristor (GTO), SiC junction field effect transistor (JFET), etc. Among them, SiC SBD and SiC MOSFET have entered the market as the first batch of commercialized devices.

For unipolar power devices, formula (1) represents the mechanism of material physical limitations.

$$R_{drift\_SP} = 4U_B^2/(\varepsilon_0\varepsilon_r\mu E_c^3) \quad (1)$$

Among them: R_{drift_SP} is the on-resistance of the device; U_B is the breakdown voltage of the device; $\varepsilon_0\varepsilon_r$ is the dielectric constant; μ is the carrier mobility; E_c is the critical breakdown electric field of the material. Formula (1) shows that the way to achieve low on-resistance is to increase the critical breakdown electric field of the material, i.e. to select the semiconductor material with wide band gap. Silicon carbide is a typical wide band gap semiconductor material. The band gap of 4H-Si C is 3.26 e V, which is much larger than 1.1 eV of silicon. Therefore, silicon carbide has higher breakdown electric field and lower intrinsic carrier concentration, which enables silicon carbide devices to work at high voltage and high temperature. Meanwhile, silicon carbide has high thermal conductivity.

Taking SBD as an example, many metals, such as nickel, gold, platinum, palladium, titanium, cobalt, can contact with silicon carbide to form Schottky barrier. The barrier height of Au/4H-SiC contacts is generally over 1eV. It is reported that the barrier height of Au/4H-SiC contacts can reach 1.73eV, and the height of Ti/4H-SiC contacts also has a wide range of Schottky barrier height of 1.1eV.6H-SiC, the lowest is only 0.5eV, the highest. It can reach 1.7eV. This is the typical width of electron tunneling. Thus, when the JBS device is positively biased, the Schottky barrier region can first enter the conduction state due to the low barrier and become the dominant device, while the PN junction does not work basically because of the high opening voltage; but in the reverse bias state, the PN junction can play the role of its high barrier, with the rapidly expanding depletion region as the Schottky barrier shielding strength under the high reverse voltage. JBS is still a majority of carrier devices. Its reverse recovery time can be reduced to several nanoseconds, only one tenth of that of silicon fast diodes and silicon carbide high voltage PN junction diodes. At present, the difficulty of JBS is that the ohmic contact of p-type silicon carbide is difficult to form, because the p-type doping of silicon carbide by ion implantation requires a high annealing temperature, and it is difficult to form P + region in silicon carbide. Experiments show that if the barrier height of these two contacts and the width of the mesa and the depth of the groove are properly matched, the reverse leakage current of the device can be greatly reduced.

2.2 Current Development of SiC Power Devices

The wide band gap and high temperature stability of SiC materials make it an incomparable advantage in power semiconductor devices. It can not only be widely used in civil power and electronics industries such as hybrid electric vehicles, motor drive, switching power supply and photovoltaic inverters, but also significantly improve the performance of military weapon systems such as naval ships, aircraft and electromagnetic guns. It will also change the future power system. Leather has a far-reaching impact. The Next Generation Power Electronics Innovation Alliance with the highest cost allocation ($140 million) aims to further promote the in-depth development of high energy efficiency and wide bandgap semiconductor power devices and power electronics devices, reduce costs substantially in the next five years, achieve large-scale industrialization, and be widely used in renewable energy generation, energy conservation, environmental protection and smart grid fields. The European Union's silicon carbide power electronics technology application program has supported the research of SiC power devices for more than ten years. Japan's new energy and industrial technology integrated switch and Japanese Prime Minister's plan have also supported the research of SiC and GaN power devices in the past decade.

3. Application Prospect of SiC Power Devices in Modern Power System

In modern power system, power electronic devices and application devices involve various aspects, including wind power generation system, photovoltaic power generation system, solid-state power electronic transformer, high voltage direct current transmission system, DC distribution system, etc. The following directions are illustrated:

(1) Solid state transformer. In recent years, with the development of distributed generation system and smart grid technology, silicon carbide based on its good performance has been widely used in the current solid-state transformer. The wide bandgap material can effectively improve the working temperature of the device. The band gaps of 6H-SiC and 4H-SiC are 3.0eV and 3.25eV, respectively. The intrinsic temperature of these two materials is above 8000 degrees Celsius, which means that the band gaps of 6H-SiC and 4H-SiC can be about 2.3eV even if the narrowest band gap is 3C-sic. In the power system, technicians use silicon carbide materials with high breakdown electric field strength to make high-voltage power switch controller. Its resistivity does not need to be too high, and the drift region or base region of silicon carbide power electronic devices does not need to be too long. By this process, not only the on-state of the device will be significantly reduced compared with the resistance, but also its working frequency will be greatly increased. Solid-state transformer is the key device of energy conversion in power electronic converter and high voltage transformer. Compared with traditional transformer, solid-state transformer has the characteristics of smaller volume, higher power supply quality, higher power supply efficiency and stable performance. The application of solid-state transformer in power system will effectively solve the existing problems of traditional transformer. The application of silicon carbide power electronic devices in solid-state transformer will simplify its structure and improve its performance.

(2) Flexible AC transmission system. Flexible AC transmission system is one of the most advanced technologies in current AC power grid. The application of silicon carbide power electronic devices in the system will be able to scientifically and efficiently control the system voltage, power and transmission quality, and effectively reduce transmission losses. The breakdown electric field strength of silicon carbide devices is 8 times that of ordinary silicon materials, and the electronic

saturation drift speed of this device is 2 times that of ordinary silicon materials. Silicon carbide power electronic devices can work for a long time and stability at high temperature because of their high thermal conductivity. In addition, silicon carbide is the only semiconductor material that can produce high-performance bulk oxide compounds by thermal oxidation. This characteristic makes it possible to fabricate power electronic devices such as MOSFBT and IGBT, which contain MOS structure, just like ordinary silicon materials. It is difficult for silicon carbide to form melt at normal pressure. When it is heated to 2400 degrees Celsius, it will sublimate. Therefore, it is very difficult or even impossible for silicon carbide to prepare single crystals by slow growth of seed crystals in the melt like ordinary crystals. Silicon carbide power devices have excellent voltage withstanding characteristics. With the development of silicon carbide devices and the improvement of manufacturing technology, more and more attention will be paid to them in FACTS technology.

(3) Static var compensator. Static var compensator is mainly used for power flow control and reactive power compensation in power system. Silicon carbide power electronic devices should effectively improve the stability and response speed of the system. Doping is the most basic technology for semiconductor device fabrication. Because the diffusion coefficient of impurities in silicon carbide devices is as low as that in silicon dioxide, at suitable diffusion temperature for silicon carbide effective impurities, silicon dioxide will lose its role of masking impurities, and the performance of silicon carbide material itself is unstable at the same high temperature. Therefore, diffusion doping is not suitable for silicon carbide devices. It is necessary to use ion implantation and accompanying doping in the preparation of materials to achieve carbonization. Conditions for silicon devices. The preparation technology of silicon carbide wafers can be divided into physical method and chemical synthesis method. Physical methods mainly include mechanical comminution and crystallization; chemical synthesis methods mainly include chemical vapor deposition and carbothermal reduction. Chemical vapor deposition and silicon carbide whisker have the same preparation process, but their process is complex and expensive, and their research and application are few at present. Effective simplification, As the switching frequency of silicon carbide power electronic devices is effectively improved, the power quality in power system can also be effectively improved.

4. Conclusion

The excellent performance of silicon carbide materials, the excellent characteristics of silicon carbide devices and their greater potential advantages inspire people's unremitting enthusiasm and hope. Therefore, the research and development of silicon carbide power electronic devices are vigorously carried out, gradually deepening and progressing faster and faster. To really enter the market and compete with silicon devices, the more important aspect is the potential of reducing power loss dramatically. Another advantage of silicon carbide and silicon in the field of power electronics technology is that they can take into account the power and frequency of devices as well as the high temperature resistance. These are the basic requirements of the further development of power electronics technology for devices, and silicon and gallium arsenide have great limitations in these areas. With the development of silicon carbide crystal growth technology and devices, silicon and gallium arsenide have great limitations. With the further improvement of parts manufacturing technology, all kinds of silicon carbide power electronic devices will be greatly improved in yield, reliability and price in the next few years, thus entering the stage of comprehensive popularization and application. This is likely to lead to a new revolution in power electronic technology. Therefore, the birth and development of silicon carbide power electronic devices is a revolution of power electronic technology at the turn of the century. Moreover, the technology of silicon carbide preparation is becoming more and more mature, and the scale of industry is expanding rapidly. The cost of silicon carbide photovoltaic inverters based on 1200V silicon carbide diodes is about 20% per year. At present, the cost of the photovoltaic inverters based on 1200V silicon carbide diodes is comparable to that of traditional inverters. They will greatly reduce volume, reduce losses, improve conversion efficiency, or develop new equipment to support transmission and transformation technologies such as flexible HVDC transmission and flexible AC transmission with higher voltage and larger transmission capacity, so as to provide a strong smart grid and accelerate China's energy strategic transformation. Core components and key equipment support. Meanwhile, the flexible DC transmission technology based on silicon carbide power electronics technology will have higher transmission voltage and transmission capacity to meet the major demands of the global energy Internet's ultra high voltage and ultra long distance transmission, and effectively cooperate with the "one belt and one way" strategy.

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