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Research on Application of Diamond MOSFET in DCDC Converter

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Abstract: This paper focuses on the industrial application of diamond power devices and DCDC converters, carries out the application research of diamond MOSFET in DCDC converters, analyzes the limitations of current silicon-based DCDC converters and how diamond MOSFET should make up for this limitation. This paper summarizes the research on the practical application of diamond power devices at home and abroad and points out that there is a gap in the application of diamond MOSFETs in DCDC converters. Diamond has the advantages of a large band gap, high carrier mobility, high temperature and high pressure resistance, so the application of diamond MOSFET in a DCDC converter can improve its operating frequency, input and output voltage and efficiency. This paper also discusses the difficulties encountered by diamond semiconductor materials and diamond power devices in the research and industrial fields, as well as the research status of diamond semiconductor materials at home and abroad, and gives the research method for the future application of diamond MOSFET in DCDC converters. The study can use the analogy of applying SiC or GaN to DCDC converters improving their performance, and redesigning the drive circuit to match the limiting performance of diamond power devices. By applying diamond MOSFET into the DCDC converter, its operating voltage, operating frequency, output power and efficiency will be greatly improved.

Keywords: Diamond, MOSFET, DCDC converter

1. Introduction

In recent years, with the increasing application complexity and performance requirements, higher requirements have been put forward for the performance of power electronic converters. The inherent limitations of silicon materials, such as narrow band gap width, low thermal conductivity, and low critical breakdown electric field, limit the circuits based on silicon power devices used in existing DCDC converters. Due to these inherent limitations, silicon power semiconductor devices struggle to meet the higher requirements of DCDC converters, particularly in terms of blocking voltage, on-resistance, operating frequency, and high temperature resistance. In this case, researchers around the world have turned their attention to diamonds, known as the "ultimate semiconductor."

Diamond semiconductor materials have great potential in applications requiring high output power, high operating frequency, and high reliability because of their unique advantages such as wide band gap, high thermal conductivity, high breakdown electric field strength, and high carrier saturation speed[2].

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At present, there are no DCDC converters using diamond MOSFETs on the market. In the face of the demand for higher performance DCDC converters generated by the vigorous development of new energy vehicles, the excellent performance of diamond is used to manufacture DCDC converters with higher output voltage, higher output power, higher operating frequency and higher efficiency, and improve their limit parameters. Get a wider range of products. In recent years, the new wide band gap materials represented by silicon carbide have attracted much attention because of their advantages. Silicon carbide power devices can reduce the converter loss and increase the power density when used in electronic converters. It has great application advantages in high temperatures, high pressure and other occasions [3]. Despite its superiority over silicon carbide in all aspects, the industrial field cannot mass-produce and apply the diamond material due to its high production cost and immature growth process.

2. .Research on diamond MOSFET power devices

2.1. Advantages of diamond materials

Diamond is one of the most important wide band gap semiconductors, with a band gap width of 5.47 eV, pure diamond does not conduct electricity when doped to show P-type or N-type semiconductor conductivity. Diamond has the highest electron saturation rate and hole mobility under a high electric field, which is suitable for making millimeter wave amplifiers and anti-radiation device materials. Diamond insulation strength is very high, 33 times that of silicon. Diamond makes it easier to produce high-power amplifiers, switches, and diodes. Diamond has the lowest dielectric constant, which is conducive to making devices mainly related to parasitic capacitance. Hydrogen terminal diamond has a negative electron affinity, which is conducive to field emission and has great potential as a cold cathode. It also has the highest Johnson Index, Keyes Index, and Baliga Index[2].

2.2. Advantages of diamond semiconductor materials

The diamond exhibits a large band gap and a very high breakdown electric field, approximately three times that of SiC and ten times that of GaN. Among known materials, diamond has the highest thermal conductivity near room temperature. Diamond in high-power device Baliga, high-frequency device Johnson, integrated logic circuit keys, and other performance indicators are much higher than other commonly used semiconductor materials. These advantages make diamonds one of the most important basic materials in the fields of high-power device development, high-frequency devices, and radiation-resistant integrated circuits. Therefore, diamond is also called "extreme electronic material"[2].

2.3. Comparison of research status at home and abroad

In the research of diamond power devices, in 2011, D.A.J.Moran et al reported for the first time a single crystal diamond device with a gate length of 50nm, which achieved a saturation leakage current of 290 mA/mm, an external transconductance of 65mS/mm, and an intrinsic transconductance of 650mS/mm[4]. In 2014, A.Daicho et al., Waseda University, deposited alumina films on the surface of the hydrogen-ended diamond to enable diamond MOSFETs to operate under a vacuum of 450°C. In 2020, the research group of M.Kasu, Saga University, Japan, prepared a diamond MOSFET with a breakdown voltage of up to 3659V[5]. In March 2024, the National Institute of Materials Science (NIMS) team in Japan developed the world's first diamond-based N-type channel-driven MOSFET, achieving a creative breakthrough in obtaining impurity elements and doping methods for low-resistivity N-type diamonds[6].

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Compared with foreign research, domestic research on diamond electronic devices started late, but the development speed is also faster. In 2019, Xidian University reported the effective diameter expansion growth of single crystal diamond for the first time in China, achieving the diamond CVD single crystal material with the largest side length (10mm) reported publicly in China, and the material quality reached the standard level of the Element Six company. In 2022, a hydrogen terminal diamond device with a figure of merit (FOM) greater than 673 V·mS/mm was reported in USTC[9]. The author quantitatively explains how temperature and carrier concentration relate to the low field mobility of two-dimensional hole gas on the surface of hydrogen-terminated diamond. In the research of high-performance diamond MOSFET devices, Xidian University has taken the lead in the research of diamond MOSFET devices with MoO3 gate media. Relevant results were published twice in the field of microelectronics, which is the top express IEEE Electron Device Letters above. Compared with the equivalent gate-long diamond MOSFET reported in the world, the on-resistance of the developed device is reduced to one-third, and the transconductance is increased by about three times. At the same time, the thermal stability of the device operating at 200°C is proved.

3. Research of DCDC converter

3.1. Basic working principle of DCDC converter

The function of the DCDC converter is to convert the input DC voltage into the output DC voltage, which can achieve the conversion of boost or buck voltage. The DCDC converter functions as a switching power supply, transforming the input DC voltage into a controllable square wave through circuit switching, and achieving energy conversion through various inductance and capacitance connection modes of the energy storage device. The topology structure's other inductor connection modes enable the realization of three distinct functions: voltage reduction, voltage boost, and voltage rise and fall. Connecting the inductor to the circuit's output load forms a Buck converter, capable of converting the output voltage to the input voltage. When the inductor is connected to the input power supply of the circuit, the Boost converter is formed, which can realize the boost conversion of the output voltage to the input voltage. When the inductor is connected to the ground of the circuit, the Buck-Boost converter is formed, which can realize the conversion of the output voltage to the input voltage[7].

3.2. Applications of DCDC converter

DCDC converter is a chip that provides a DC power supply in the power management chip, which is widely used in various electronic products and is truly the heart of electronic products. The high power density of the DCDC switching power supply makes it more suitable for applications that require high current, high voltage, high efficiency, and miniaturization, such as base stations, data centers, robots, new energy vehicles, and other emerging industries. According to the future think tank data analysis, in the next five years, the global DCDC market size will exceed 7 billion US dollars, and the Chinese market demand will exceed 30%.

3.3. Challenges in the research of DCDC converters

Existing DCDC converters generally use circuits based on silicon power devices, which are limited by the inherent limitations of silicon materials, such as narrow band gap width, low thermal conductivity, and low critical breakdown electric field, making it difficult for silicon power semiconductor devices to meet the higher requirements of DCDC converters on power devices in terms of blocking voltage, on-resistance, operating frequency, and high-temperature resistance[1]. In recent years, the new wide-bandgap materials represented by silicon carbide have attracted much

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attention due to the superiority of their materials. If using silicon carbide materials to make power devices, they have high blocking voltage, low on-loss, high temperature tolerance, and high-speed switching. This can lower converter loss and increase power density when used in electronics and electronic converters. This technology offers significant benefits in situations involving high temperatures, high pressure, and other similar conditions. However, with the development of technology, the requirements for device performance have further increased. Higher operating frequency, higher voltage and temperature resistance, higher output power, and lower on-resistance, require further iterations of the device.

4. Suggestion

Although diamond MOSFET is not currently used in DCDC converters, the research of using SiC MOSFET or GaN devices in the power switch tube of the main circuit of a DCDC circuit has been very mature, so to further improve the operating frequency of the circuit, to reduce the on-off loss and switching loss of the switching tube and to enhance the working ability and stability of the switching power supply in harsh environments such as high temperature, you can refer to the situation of SiC and GaN, the diamond MOSFET is applied in the power switching tube of the main circuit[8]. Specifically, Simulink can be used for circuit simulation first. The Simscape Electrical component library builds the LLC resonant converter simulation diagram of the diamond MOSFET based on the parameters of high-voltage and high-power diamond MOSFET devices provided by the laboratory. Based on the performance parameters of diamond MOSFET, the circuit structure is adjusted to find the circuit structure most suitable for diamond MOSFET. The author analyzes how the parameters of the diamond MOSFET affect the output characteristics of the DCDC converter. Among them, the MOSFET's operating frequency increases the operating frequency of the converter, the on-resistance decreases the switching loss and on-loss of the converter, the power density increases the efficiency of the converter at all levels, the voltage tolerance increases the simplification of the circuit structure and the operating voltage increases. Next, analyze the loss of the built circuit: with the development of power electronics, switching converters continue to develop in the direction of high efficiency and high power density, so it is particularly important to analyze the loss of each component to better design switching converters. The loss of the resonant converter mainly includes switching tube loss, rectifier diode loss, and magnetic component loss, which should be calculated separately[8].

5. Conclusion

In modern society, switching power supply has become one of the indispensable pillars of human life. With the advent of the information age and the breakthrough of 5G technology, more and more high-tech electronic devices are changing our lives but also putting forward new challenges for switching power supplies. Sophisticated electronic devices have more precise power supply requirements, and their diverse needs expand the market for multi-output switching power supplies. At the same time, the introduction of the third generation of semiconductor materials has ushered in a revolutionary development opportunity for power devices, and switching power supplies has a new development direction. To improve the performance of the switching power supply, diamond MOSFET is proposed to be used in the DCDC converter.

This paper presents the background, significance, and limitations of the current switching power supply, symbolized by the DC-DC converter, in the first chapter. The second chapter introduces the advantages of diamond semiconductor materials and their power devices, as well as the research on diamond materials both domestically and internationally. The paper highlights the limitations of diamond material growth and device manufacturing. Next, the paper introduces the basic working principle of the DCDC converter and the wide application of the DCDC in today's society and points out the dilemma of switching power supply represented by the DCDC converter.

In the third chapter, this paper introduces specific suggestions for the application of diamond MOSFET into a DCDC converter, which can learn from the more mature application mode of SiC or GaN MOSFET, and carry out simulation, experimentation and loss analysis concerning laboratory data.

At present, limited by the slow progress of diamond production process research, the cost of large-scale mass production of diamond MOSFET is too high, resulting in no research on the application of diamond into DCDC converters. In the future, researchers can devote themselves to studying the material growth of diamonds and the field of device fabrication or the application of diamond MOSFET into the switch tube of the DCDC converter and the change of the structure of the drive circuit.

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