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Cryogenics Power Electronics: Analyzing the Potential of Gallium Nitride (GaN) for High-Efficiency Energy Conversion and Transmission

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Abstract: Power electronic devices continuously evolve towards higher conversion efficiency and lower energy loss, promoting efficient energy use and sustainable development. However, the rising temperature of the working device usually leads to unavoidable energy loss. To address this issue, cryogenic power electronics have attracted increasing attention from researchers. The use of low temperatures in these devices minimizes thermal losses, improving their efficiency and performance. Additionally, the development of new technology, such as superconductivity, and complex application environments also intensify the demand for cryogenic power electronic devices. The purpose of this paper is to critically analyze the challenge of cryogenics power electronics and provide some solutions, especially for Gallium Nitride (GaN) devices. By reviewing published articles, this article believes that GaN has great potential to address the obstacles in developing cryogenic electronic power. In the first section, the development status of cryogenics power electronics and current research on GaN devices will be introduced, and some challenges will also be given. The second part of this article will explore the feasibility of developing GaN technology to solve these challenges. Finally, a conclusion will be drawn.

Keywords: Gallium Nitride, Cryogenics power electronics, Silicon, Silicon carbide, Cryogenic temperature

1. Introduction

In recent years, research on low-temperature electronic power has attracted more and more attention. In transportation, for example, superconducting materials are used to power magnetic levitation (Maglev) systems, where they enable nearly frictionless and highly efficient transportation. Similarly, in the maritime industry, ships equipped with superconducting motors have shown remarkable improvements in operational efficiency, achieving lower energy consumption and reduced emissions compared to traditional motor systems. Furthermore, superconducting cables are being explored to reduce energy losses in power grids. These cables, which carry electricity without resistance, can transport large amounts of power over long distances with low energy dissipation, improving the efficiency of power transmission. This has the potential to greatly enhance the efficiency and sustainability of electricity distribution networks [1]. Beyond superconductivity, the effectiveness of low-temperature heat dissipation by refrigerant material has become more important. These materials

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keep electronic components at their optimum operational temperature, enabling them to last longer and perform better [2]. Since equipment will work at cryogenic temperatures, materials such as refrigerant and other components must be selected to maintain performance without thermal failure. Combining superconducting materials and novel methods of heat management could change the way power systems, creating new opportunities for power electronics for transport, industrial, and grid systems.

2. Common low-temperature materials

There are several typical materials of cryogenics power electronics, such as GaN, silicon (Si), and silicon carbide (SiC) [3]. Among them, GaN shows relatively good performance.

One of the key advantages of GaN over traditional semiconductors like Si is its ability to maintain stable performance under cryogenic conditions. According to Hassan et.al, GaN is more stable than other materials when the device performs at low temperatures, as shown in Table. 1 [4]. That is because GaN has constant

Table 1: Performance of different devices at low temperature

Device Type	On-State Resistance	Threshold Voltage	Breakdown Voltage	Switching Performance
GaN HEMT	↓	Stable	Stable	↑
SiC-MOSFET	↑	↑	Stable	↓
Si-MOSFET	↓	↑	↓	↑
Si-IGBT	↓	↑	↓	↑

breakdown voltage and no carrier freeze out [5]. Additionally, compared with traditional semiconductors like Si, GaN has a larger bandgap, which allows to produce of higher frequency and more compact devices [6]. In practical applications, GaN is proven to be effective in reducing losses and improving efficiency when working at a low temperature. Yang et.al provide a GaN High Electron Mobility Transistors for Cryogenically Cooled Solid-state Circuit Breaker, which can achieve interrupt 1000A (about ten times as much as solid-state circuit breaker current) at -180℃[7]. Wadsworth et.al mention that GaN-based cryogenic power converters can work at a minimum temperature of 77K in the existing records, and they bring out a GaN half-bridge which can work normally at 44K, even having the potential to extend its working temperature to 77K. In this device, its losses only include conduction losses and high side switch [8]. These advances prove that GaN has great potential to minimize losses and increase the efficiency of low-temperature electronic systems. However, it is also subject to some conditions, especially in devices with high bus voltages, where its blocking voltage ability can be an issue. While GaN’s efficiency, low losses, and high thermal conductivity make it an attractive option for low-temperature environments, its relatively lower blocking voltage compared to other materials such as SiC can limit its performance in high-voltage systems. This limitation becomes especially significant in power electronics that are expected to manage substantial voltage levels. Therefore, Si and SiC materials with more mature manufacturing processes are still the standard choice for most applications because of their established production techniques. Particularly, SiC has an advantage over GaN in terms of its ability to handle higher blocking voltages, making it better suited for use in high-voltage systems, such as power grid applications, electric vehicles, and industrial machinery. SiC's higher breakdown voltage and robustness at high temperatures give it a clear edge in these high-power, high-voltage environments. Nonetheless, the development of GaN technology and its cryogenic temperature capability still have a bright future for GaN-based power electronics at low-temperature applications

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[3]. As GaN manufacturing technology and material quality continue to advance, it is expected that GaN's blocking voltage limits will continue to improve. GaN's unique advantages, such as stability at low temperatures, low power consumption and fast switching capabilities, make it ideal for emerging applications in cryogenic power electronics, complementing or even exceeding the performance of traditional materials such as Si and SiC in certain environments. These include areas such as aerospace, high-energy physics, and next-generation communications systems.

3. Challenges

Cryogenic power electronics, which work in extremely low-temperature environments, have advantages for applications in different areas, including transportation, energy systems, and high-performance computing. However, the development and deployment of these technologies face several challenges, including material selection and thermal management.

3.1. Material selection

Materials are one of the main issues. In cryogenics power electronics, the working temperature usually reaches -150℃. At such temperatures, the electrical conductivity and stability of many typical materials will be affected, resulting in lower effectiveness in power devices. For example, Si may have problems like unstable currents and increased energy losses at low temperatures. Although superconducting materials have the advantage of zero resistance at low temperatures, their characteristic of being highly sensitive to temperature and magnetic fields might limit the possibility of wide application. They are highly sensitive to both temperature fluctuations and magnetic fields, and any non-ideal conditions can cause them to lose their superconducting properties. This sensitivity limits the widespread application of superconductors in practical systems, as maintaining the strict conditions required for superconductivity can be challenging and costly [9]. Therefore, selecting appropriate materials that maintain stable performance under cryogenic conditions is crucial for ensuring the reliability and efficiency of power electronics.

3.2. thermal management

Another critical challenge in cryogenic power electronics will be thermal management. Cryogenics power electronic devices have to work at specific temperatures which greatly affects the efficiency. However, several factors can influence the temperature of these devices, including self-heating within the components themselves. Self-heating comes from the electrical current passing through the device, which generates heat. At low temperatures, even small amounts of heat generated within the device will cause significant temperature fluctuations, which may impact the stability and efficiency of the device [10]. In practical applications, efficient thermal management systems are necessary to ensure that the devices remain within their operational temperature range. This requires innovative solutions to dissipate heat effectively, preventing the device from overheating.

4. Solution

To address the challenges of cryogenic power electronics, particularly material selection and thermal management, GaN could be proposed as one of the feasible solutions.

Traditional semiconductor materials such as SiC and Si, showing decreased performance at low temperatures due to changes in carrier mobility and other temperature-relevant factors. Specifically, SiC will have increased conduction losses at low temperatures because of reduced carrier mobility, which leads to a reduction in overall efficiency. On the contrary, GaN does not have such problems and is not limited by carrier freeze-out at cryogenic temperatures, making it a more reliable and

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efficient choice for low-temperature applications [11]. Furthermore, GaN has a larger band gap (around 3.4 eV), which enhances its stability and reduces its temperature sensitivity. A larger band gap means that GaN can work at higher voltages, frequencies, and lower temperatures. This property makes GaN an ideal material for power electronics that need to operate reliably in extreme environments, such as cryogenic systems. Chen et.al have proved that the specific on-state-resistance of Si MOSFETs increases when the temperature is lower than 100K, while GaN HEMT stays decreasing. For GaN HEM, on-resistance was reduced by more than 5 times compared with room temperature conditions, having the lowest on-resistance ratio at low temperature [12].

The ability to handle high voltages and low temperatures without performance reduction allows GaN-based devices to achieve higher efficiency in low-temperature operations, making them suitable for critical applications in power grids, transportation, and other fields requiring high-performance electronics.

Effective thermal management is important to ensure the longevity and efficiency of electronic devices, especially in cryogenic power systems. One key aspect of thermal management is controlling both external heat dissipation and the internal heat generated by the devices themselves. Self-heating in devices can be a significant issue, especially at low temperatures, where even minor fluctuations in temperature can cause performance degradation or even failure. GaN devices are particularly advantageous in this part because they generate less heat during operation compared to traditional semiconductors like Si and SiC. This is due to GaN's high efficiency and low energy losses during switching and conduction processes. As a result, GaN-based devices are better equipped to manage their heat generation, leading to improved thermal stability and reduced need for complex cooling systems. Furthermore, the GaN device allows the design of more compact and lightweight devices. This is an effective way to dissipate heat by reducing surface area, which further enhances the efficiency of the thermal management system. The ability to create smaller, more efficient devices with reduced heat generation means that GaN can contribute to more streamlined designs in cryogenic power electronics, which is crucial for applications where space, weight, and efficiency are critical considerations [6].

Overall, GaN shows great potential in overcoming the key challenges of cryogenic power electronics. Its excellent material properties, including high thermal conductivity, wide band gap, and stable performance at low temperatures, make it an ideal choice for designing high-efficiency, high-feasibility power devices that can work effectively in extreme environments. As research and development continue, GaN is expected to play an important role in advancing cryogenic power electronics, offering solutions for applications that need high reliability, energy efficiency, and low-temperature operation.

5. Conclusion

This article introduced cryogenic power electronics and focused on discussing the main challenges and potential solutions The primary challenges identified include material instability at low temperatures and thermal management. Among the different materials explored for low-temperature electronics, GaN has been an appropriate choice due to its excellent performance characteristics in cryogenic environments. This paper highlighted GaN's ability to avoid carrier freeze-out, its large band gap, and its inherent stability at low temperatures, which collectively address the issues of unstable material properties and inefficient thermal management. These properties make GaN an ideal material for designing power electronic devices that can operate efficiently and reliably in low-temperature conditions. However, this paper is based on theoretical knowledge and existing articles, lacking support for experimental verification. Experimental verification is crucial to assess the actual performance of GaN-based devices under cryogenic conditions and to determine how they compare to traditional materials like Si and SiC in practical applications. This would also help identify potential challenges that may not be evident in theoretical models or simulations. In the future, GaN-based devices should be paid more attention to develop higher efficiency and lower loss cryogenic power electronic devices. With the growing demand for efficient energy systems, particularly in industries like aerospace, medical technologies, and power grids, GaN-based cryogenic power electronics could play a significant role in meeting these needs. The future of this field lies in advancing theoretical knowledge into practical, real-world solutions that offer higher efficiency, reduced losses, and reliable operation at low temperatures.

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