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Applications and challenges of Silicon Carbide (SiC) MOSFET technology in electric vehicle propulsion systems: A review

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Abstract. Silicon Carbide (SiC) MOSFET technology plays a pivotal role in the drive systems of electric vehicles (EVs), offering key applications and facing significant challenges. This paper provides an overview of the fundamental principles and characteristics of SiC MOSFETs, highlighting the unique properties of SiC materials. It delves into the critical applications of SiC MOSFETs in electric vehicle drive systems, including motor drives and inverters, and analyzes the advantages of using SiC MOSFETs for efficient energy conversion at high temperatures. The paper also discusses the key challenges faced by SiC MOSFET technology, such as stability issues under high-temperature environments, avalanche breakdown and tolerance issues affecting power supply reliability, and manufacturing cost and consistency issues that limit widespread application. Innovative solutions to these challenges are explored, including strategies for improving stability under high temperatures, techniques for suppressing avalanche effects and enhancing power supply reliability, and innovations in manufacturing processes to reduce costs and improve consistency. The paper concludes by summarizing the crucial role of SiC MOSFET technology in electric vehicle drive systems, emphasizing the importance of innovative solutions to address its challenges, and looking forward to its continued contribution to technological advancements in the field of electric vehicles.

Keywords: Microelectronics, SiC MOSFET, Electric Vehicle (EV), High-Temperature Stability, Avalanche Effects.

1. Introduction

In recent decades, the automotive industry has witnessed a profound paradigm shift towards sustainable transportation, primarily driven by the advancement of EVs [1]. This transition is fuelled by the imperative to mitigate environmental degradation and reduce dependence on fossil fuels. In response to this imperative, extensive efforts have been directed towards various facets of electric mobility, including battery technologies, charging infrastructure, and power electronics, yielding remarkable progress. The surge of interest and investment in EVs has propelled the development of multiple ground-breaking technologies [2]. One particularly promising innovation in the context of power electronics is the development of Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) technology. In comparison to traditional silicon-based semiconductors such as Insulated Gate Bipolar Transistors (IGBTs), SiC MOSFETs present a multitude of enhancements. These include

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the ability to operate at higher temperatures, achieve faster switching speeds and frequencies, and represent the next evolutionary leap in the domain of electric propulsion systems. This assertion is supported by a growing body of research in the field [3]. Indeed, within the broader scope of microelectronics, SiC MOSFETs have emerged as a disruptive force capable of revolutionizing power electronics [4]. This paper delves into the transformative potential of SiC MOSFET technology within the context of electric vehicle propulsion systems. By examining the unparalleled attributes and manifold applications of SiC MOSFETs, as well as the challenges they face and innovative solutions therein, this paper aims to shed light on the pivotal role of SiC MOSFETs in the ongoing evolution towards sustainable transportation. The research holds significant societal value as it contributes to the transition towards sustainable transportation, reducing greenhouse gas emissions and advancing eco-friendly electric vehicle technology. It also benefits the microelectronics field by offering insights into material science, device physics, and manufacturing processes. Moreover, it provides valuable knowledge for those interested in this field of research, helping them stay at the forefront of technological innovation in semiconductor technology.

2. Basic principles and characteristics of SiC material and SiC MOSFET

Silicon carbide (SiC) is a compound material that has many remarkable properties. SiC is a classical polytypic substance existing in more than 250 polytypes. The most frequently studied polytypes for SiC devices are 6H-SiC, 4H-SIC, and 3C-SiC [5]. Among them, 4H-SiC the most used and established-material, has been developed exclusively and is also more readily available [6].

According to the Mohs scale of mineral hardness, SiC (silicon carbide) has a hardness of 9.5, which is very close to the hardness of diamond (10) and cubic boron nitride (9.75) [7]. SiC also has excellent thermal conductivity, electrical conductivity, and resistance to oxidation and corrosion. Its ability to efficiently transfer heat, lower operating temperatures, and enhance overall system efficiency and reliability makes it particularly valuable. Furthermore, SiC maintains excellent current transmission even in high-voltage or high-temperature environments, making it well-suited for power electronic devices.

A MOSFET, functioning as a type of transistor, manages current flow by applying a voltage to the gate terminal to create an electric field that modulates channel conductivity. The MOSFET’s efficacy, however, can never attain one hundred percent due to inevitable energy losses, mainly through heat generation during operation. These energy losses lead to a gradual rise in temperature, influencing device properties, particularly electrical characteristics [8]. Notably, SiC power MOSFETs exhibit a distinct advantage over Si power MOSFETs; even as Si power MOSFETs reach saturated current and calculated voltage conditions, the drain current of SiC power MOSFETs continues to rise with increased applied drain voltage. As a result, SiC power MOSFETs show remarkable high-temperature operational capabilities compared to Si power MOSFETs.

The elevated switching speed inherent to SiC MOSFETs allows for higher operational frequencies and smaller passive components, as highlighted in the papers by Liu et al. and Editorial Staff [8-9]. This dynamic characteristic not only fosters compact and lightweight power converters but also substantially augments dynamic performance and control precision in motor propulsion systems. Furthermore, the confluence of augmented breakdown voltage and superior thermal conductivity, as expounded upon in references like the paper by Langpoklakpam et al., imbues SiC MOSFETs with the resilience to operate seamlessly under elevated temperatures and voltages, mitigating cooling exigencies and engendering heightened device reliability, durability, increased power outputs, and expedited battery charging [10].

These features allow SiC MOSFETs to reduce the size, weight, and cooling requirements of power converters and inverters, which are essential components of electric vehicle propulsion systems.

3. Key applications of SiC MOSFETs in EV propulsion systems

Electric vehicle propulsion systems serve as the fundamental constituents within battery-electric vehicles, effecting the conversion of stored electrical energy from the battery into mechanical power to propel the wheels. Conversely, they also facilitate the transformation of kinetic energy into electrical energy during regenerative braking maneuvers. The main components of EV propulsion systems are the power electronics, electric motor, transmission, and battery [11]. Among these components, the power electronics play a vital role in controlling the motor speed, torque, and efficiency, as well as managing the battery charging and discharging processes. The power electronics consist of several converters and inverters that switch the direct current (DC) from the battery to alternating current (AC) for the motor, or vice versa for the charger [12].

SiC MOSFETs have been widely applied in different electric vehicle scenarios, such as traction inverters, on-board chargers, and off-board chargers. Traction inverters are the key components that drive the traction motor of the vehicle. They convert the DC voltage from the battery to three-phase AC voltage for the motor. By replacing silicon IGBTs and diodes with SiC MOSFETs in traction inverters, the efficiency can be improved by 2% to 8%, depending on the bus voltage and load condition [12]. Moreover, SiC MOSFETs can reduce the size and weight of the traction inverters by 50% to 70%, and simplify the cooling system by using liquid cooling instead of air cooling [13].

On-board chargers are used to charge the batteries of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) from the AC power grid. They consist of a rectifier stage that converts AC to DC and a DC/DC converter stage that regulates the DC voltage level for the battery. SiC MOSFETs can improve the efficiency of on-board chargers by 1% to 3% and reduce the size and weight by 30% to 50% compared with silicon IGBTs or MOSFETs [12]. Furthermore, SiC MOSFETs can enable higher switching frequencies and higher power factors for on-board chargers, which can reduce passive components and harmonics [14].

Off-board chargers are external devices that provide fast DC charging for EVS. They consist of a rectifier stage that converts AC to DC, a power factor correction (PFC) stage that improves the power quality, and a DC/DC converter stage that regulates the DC voltage level for the battery. SiC MOSFETs can increase the efficiency of off-board chargers by 2% to 4%, and reduce the size and weight by 40% to 60%, compared with silicon IGBTs or MOSFETs [12]. Additionally, SiC MOSFETs can enable higher power ratings and higher charging currents for off-board chargers, which can shorten the charging time and extend the driving range [15].

4. Challenges and innovative solutions in SiC MOSFET technology

SiC MOSFETs have shown great potential for high-performance power applications, but they also face some challenges that need to be addressed to ensure their reliability, efficiency, and cost-effectiveness.

4.1. High-temperature stability challenges

One of the advantages of SiC MOSFETs is their ability to operate at high temperatures, which can reduce cooling system requirements and increase power density. However, high-temperature operation also poses some stability challenges for SiC MOSFETs, such as thermal runaway, gate oxide degradation, and parasitic bipolar junction transistor (BJT) activation [16]. Thermal runaway is a phenomenon where the device temperature increases rapidly due to positive feedback between the on-state resistance and the junction temperature, leading to device failure. Gate oxide degradation is caused by the high electric field and temperature stress on the gate oxide layer, resulting in interface traps, oxide charges, and breakdown. Parasitic BJT activation is a phenomenon where the parasitic BJT formed by the p-type body region, the n-type drift region, and the n-type source region of the MOSFET is turned on due to a high injection of minority carriers from the source to the body region, causing a short circuit between the drain and the source.

To overcome these challenges, several solutions have been proposed or implemented in SiC MOSFET technology. One approach involves optimizing the device’s structural configuration and layout to mitigate issues such as current crowding and the formation of hotspots [17]. Additionally, temperature sensors coupled with feedback control circuits are utilized to actively monitor and regulate the device’s operating temperature.

For enhancing gate oxide reliability, a range of methodologies have been explored. These encompass the utilization of high-quality gate oxide materials and refined manufacturing processes [18].

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Appropriate gate bias and gate drive circuits are employed to alleviate the stress induced by the electric field [10]. Protection mechanisms, including gate clamps and zener diodes, are integrated into the design to avert potential damage due to overvoltage and electrostatic discharge (ESD).

To suppress the parasitic BJT activation, which can cause device degradation and failure, different approaches have been proposed and implemented. One of the strategies is to increase the body doping concentration of the SiC power devices, which can effectively raise the base-emitter turn-on voltage of the parasitic BJT. By doing so, the parasitic BJT can be prevented from being activated under normal or abnormal operation conditions, and the reliability and robustness of the SiC power devices can be improved [19]. Another approach integrates a Schottky barrier diode (SBD) between the source and the body region to impede the injection of minority carriers [20].

4.2. Avalanche effects and enhancing power supply reliability

One of the challenges of SiC MOSFET technology is ensuring its reliability and robustness under avalanche conditions, which occur when the device is subjected to a high voltage stress beyond its breakdown voltage. Avalanche breakdown can cause severe damage to the device, such as gate oxide failure, local hot spot formation, and parasitic bipolar junction transistor (BJT) latching [17][21]. Therefore, it is important to understand the mechanisms and factors that affect the avalanche capability of SiC MOSFETs, and to design appropriate protection circuits and strategies to enhance the power supply reliability.

Several studies have investigated the performance and failure modes of SiC MOSFETs under avalanche conditions, using experimental methods and simulation tools. For example, the paper by Luo et al. conducted unclamped inductive switching (UIS) tests on commercial SiC MOSFETs and analyzed the breakdown voltage, avalanche energy, heat power dissipation, and gate oxide integrity [17]. Their findings revealed a direct correlation between the breakdown voltage and the magnitude of avalanche energy, and also demonstrated that the SiC material inside the device could be burned down due to a local hot spot with extremely high heat power dissipation. Additionally, their observations highlighted a notable phenomenon: the gate oxide’s failure under avalanche conditions due to the intricate interplay between elevated temperatures and the prevailing electric field. This interaction culminated in the occurrence of a short circuit between the gate and drain terminals.

The paper by Nida et al. investigates the current capability of SiC MOSFETs under avalanche conditions by using UIS measurements and electrical transport simulations [21]. They identified the current paths and maximum avalanche currents, and provided insight into the design limits of the devices. They showed that the energy capability of SiC MOSFETs was reduced for avalanche currents >52 A due to the latching of the parasitic BJT, which also limited the maximum switchable current to ≤102 A.

Based on the findings, some possible solutions to improve the avalanche reliability of SiC MOSFETs are:

1) Optimizing the device structure and parameters, such as JFET region width, channel length, doping concentration, and gate oxide thickness, to reduce the electric field stress and enhance the breakdown voltage [22].

2) Applying proper gate driving techniques to control the switching speed and avoid excessive dv/dt and di/dt [23].

3) Using thermal management methods to reduce the temperature rise and avoid thermal runaway [24].

4.3. Manufacturing cost and consistency considerations

Another challenge of SiC MOSFET technology is to lower its manufacturing cost and increase its consistency, which are crucial for its widespread adoption in various applications. Compared to conventional silicon (Si) power devices, SiC MOSFETs have higher costs due to several factors, such as the several aspects mentioned in these researches [25]:

(1) The high cost of SiC substrates, which are produced by a sublimation process that requires high temperature, a long growth time, and low yield .

(2) The high cost of epitaxy and fabrication processes, which require higher temperature and more expensive consumables than Si processes.

(3) The low quality and uniformity of SiC material result in various defects that affect the device's performance and reliability.

Therefore, it is necessary to develop innovative solutions to reduce these costs and improve these qualities, such as:

(1) Scaling up Wafer Size: The enlargement of wafer dimensions from 150 mm to 200 mm or beyond merits substantial attention. Such upscaling can significantly augment the number of devices per wafer, thereby leading to reduced fabrication costs.

(2) Optimizing Sublimation Process Parameters: Optimizing sublimation process parameters is crucial for enhancing substrate quality and yield, leading to cost efficiency.

Other measures briefly mentioned include enhancing epitaxy quality, improving fabrication quality through advanced techniques, and increasing vertical integration of substrate production and device fabrication. These measures collectively hold the potential to further advance the field.

5. Future development trends and prospects

SiC MOSFETs are widely recognized as the next-generation power devices for electric vehicle. These devices contribute to the reduction in size, weight, and cost of powertrain inverters, onboard chargers, and DC/DC converters while also enhancing driving range, charging speed, and vehicle reliability [12]. Prominent automotive manufacturers like Tesla and Ford have already embraced or outlined plans to integrate SiC MOSFETs into their electric vehicle models [26]. However, challenges including high costs, supply chain limitations, standardization gaps, and reliability concerns continue to impede the widespread adoption of SiC MOSFETs in electric vehicle applications. Further research and development endeavors are therefore imperative to address these challenges and facilitate the widespread commercialization of SiC MOSFET technology within the EV domain.

6. Conclusion

This paper scrutinizes SiC MOSFET technology, its applications, and challenges in EV propulsion systems. It discusses the superiority of SiC MOSFETs over traditional silicon-based devices in efficiency, power density, temperature tolerance, and fast charging. The paper explores innovative solutions for technical issues faced by SiC MOSFETs in EV applications, such as high-temperature stability, avalanche breakdown, reliability, manufacturing cost, and process consistency. It underscores the potential impact and future prospects of SiC MOSFET technology in the EV field, including trends in efficient energy conversion, lightweight design, and bidirectional power flow. The paper concludes that SiC MOSFET technology is crucial for advancing EV propulsion systems due to its performance, reliability, and cost-effectiveness. It also identifies opportunities for future research and improvement, including further empirical validation through comprehensive experimentation and real-world case studies, investigation of market demand and feedback from EV manufacturers to align technology development with practical needs, and focus on the sustainable integration of SiC MOSFET technology into broader energy systems with environmental considerations.

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