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A systematic analysis of wide band gap semiconductor used in power electronics

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Abstract. In recent years, the field of power electronics has witnessed a significant shift towards the adoption of wide bandgap (WBG) materials, marking a pivotal change in the design and efficiency of electronic devices. This paper presents a comprehensive systematic analysis of wide bandgap materials and their semiconductor applications in power electronics. Initially, the paper provides essential background information, elucidating the emerging importance of WBG materials in modern electronics. It then delves into various types of wide bandgap semiconductors, examining their fundamental operating principles and theoretical underpinnings. Subsequent sections of the paper highlight the advantages of using wide bandgap semiconductors, including their superior performance and efficiency benefits. The discussion extends to practical implementations, showcasing several existing applications of wide bandgap semiconductors in diverse power electronics scenarios. Additionally, this paper critically addresses the prevailing challenges and obstacles encountered in the application and manufacturing processes of these materials. Moreover, it offers insightful predictions about the future trajectory and potential advancements in wide bandgap device technology. The paper culminates with a concise conclusion summarizing the impact and prospects of wide bandgap devices in the realm of power electronics.

Keywords: Wide Bandgap, Power Electronics, Semiconductors

1. Introduction

The evolution of microwave and optoelectronic devices has ushered in escalating demands for power electronics applications, especially in high-power, high-frequency, high-speed, and high-temperature circumstances, often required for operation in harsh environments [1]. Notably, advanced systems like high-performance military aircraft and supersonic engine monitoring systems necessitate long-term operation at 300 ℃, a temperature far beyond the capability of standard devices operating at 100 ℃. Even in the hostile conditions of interstellar voyages, with Mercury's surface soaring to 370 ℃ and Venus registering a searing 450 ℃, existing silicon batteries are limited to 200 ℃, while GaAs batteries suffer reduced efficiency beyond 200 ℃ [2]. The communication sector also demands higher frequencies and greater power, unattainable by current Si or GaAs devices.

In space exploration, the requirement to cool devices to the Si-tolerated temperature of 125 ℃ mandates complex cooling systems. However, envisioning devices that can function at 325 ℃ not only eliminates the need for extensive cooling but also reduces unmanned spacecraft volume by a staggering

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60% [3]. The contemporary era necessitates high-temperature semiconductor materials, heralding an exciting time for semiconductor researchers as recent years witness rapid progress in high-temperature semiconductor research.

The breakthrough in silicon carbide (SiC) refining and manufacturing technology emerged in the 1990s, leading to the introduction of SiC-based Schottky diodes in the early 21st century. These diodes outperformed silicon counterparts, swiftly finding application in power electronic devices, with benefits outweighing cost concerns. Similarly, gallium nitride (GaN) semiconductor manufacturing saw breakthroughs since the 1990s, enabling the fabrication of devices on various substrates using a real spinning process. GaN devices, with superior high-frequency characteristics compared to SiC, garnered increased attention.

2. Theoretical Analysis of Wide Bandgap Devices in Power Electronics

2.1. The Definition of The Wide Bandgap Semiconductor

The concept of a band gap, also known as an energy gap, refers to the required energy that propels an electron from the valence band to the conduction band [4]. This gap, often termed the forbidden band or energy gap, represents a zone in a semiconductor where, under typical conditions, electrons are not present. The breadth of this gap is crucial in determining the electrical characteristics of a semiconductor. A broader gap indicates a higher barrier for electron movement from the valence to the conduction band, thus decreasing the material's conductive properties. Conversely, a narrower gap suggests a lower barrier, facilitating easier electron transition into the conduction band and thereby increasing conductivity. Semiconductors with a wide bandgap consist of materials exhibiting a greater bandgap than conventional substances. Common semiconductor materials, like silicon, typically have a bandgap ranging from 0.6 to 1.5 electron volts (eV). In contrast, wide bandgap materials possess a bandgap exceeding 2eV. This characteristic allows semiconductors made from these materials to function effectively under conditions of higher voltage, frequencies, and temperatures, as they require more energy for electron transitions in the valence band [5]. Silicon Carbide (SiC) and Gallium Nitride (GaN) are among the most prominent and extensively utilized materials in the realm of wide bandgap semiconductors.

2.2. Kinds of Wide Bandgap Devices

There are several common types of semiconductors using wide bandgap materials.

1) Gallium Nitride (GaN) Devices: GaN semiconductors are one of the most used devices, especially in power electronics and radiofrequency (RF) applications. Transistors using GaN are employed commonly in power supplies, RF amplifiers and advanced radar systems. It is famous for its free-electron velocities, which is significantly beneficial to high frequency conditions. What makes GaN semiconductors extraordinary is that it has extremely low switching loss.

2) Silicon Carbide (SiC) Devices: SiC semiconductors especially excel in conductivity under high temperature circumstances. So, they are used in high power density and temperature applications like electric vehicles' power inverter and some motor in industry.

3) Diamond Semiconductor Devices: Diamond Semiconductors can be applied to not only high thermal condition but also wherever needed for high breakdown voltage. However, the application is still developing and not even wide yet.

4) Aluminum Nitride (AlN) Devices: AlN semiconductors are used more widely in high temperature sensors.

5) Gallium Arsenide (GaAs) Devices: Need to mention, GaAs devices are considered more as a compound semiconductor, because it doesn't have as wide bandgap as other WBG materials. Nevertheless, it still has a bandgap which is wider than other common semiconductor materials like silicon, enabling it to be employed in optoelectronic devices. Also, some transistors are composed of GaAs to make themselves heterojunction bipolar transistors, which can be used in high performance devices like amplifiers and microwave devices.

There are other wide bandgap materials like Zinc Oxide (ZnO) and Gallium Oxide (Ga2O3). Due to the property of wide bandgap, they all have the similar characteristics. The properties of major wide bandgap materials is shown in table 1.

Table 1. Properties of Major Wide Bandgap Materials [6]

Property	Si	6H-SiC	4H-SiC	GaN	Diamond
Bandgap Eg(eV)	1.1	3.03	3.26	3.45	5.45
Dielectric Constant,ε_r	11.9	9.66	10.1	9	5.5
Breakdown Field, Ec(kV/cm)	300	2500	2200	2000	10000
Electron mobility μ_n(cm2/V-s)	1500	500	1000	1250	2200
Hole Mobility μ_n(cm2/V-s)	600	101	115	850	850
Thermal Conductivity, λ(W/cm-K)	1.5	4.9	4.9	1.3	22
Thermal Expansion(x10-6)/°K	2.6	3.8	4.2	5.6	1-2
Saturated E-Drift Velocity, Vsat(x107cm/s)	1	2	2	2.2	2.7

2.3. Benefits of Wide Bandgap Devices

Semiconductors with wide bandgaps present numerous benefits, notably their capacity to function at elevated temperatures (as high as 300 °C), which is particularly advantageous in demanding environments such as those encountered in military applications. Their resilience to extreme temperatures also permits usage at escalated power levels. Moreover, the substantial bandgaps in these materials result in an electrical field density nearly tenfold greater than that found in traditional semiconductors, facilitating their usage under considerably higher voltages and currents. These attributes render wide bandgap semiconductors indispensable in areas like military operations, radio technology, and power conversion systems. The U.S. Department of Energy recognizes their critical role in the advancement of future electrical infrastructures, renewable energy technologies, and high-power transportation means, including plug-in electric vehicles and electric-powered trains. Furthermore, the high velocity of free electrons in these semiconductors contributes to more rapid switching capabilities, which proves beneficial for radio applications. A singular wide bandgap device can efficiently function as an integrated radio system, removing the necessity for distinct signal and radio-frequency components, while operating at elevated frequencies and power outputs [7].

3. Application Examples of Wide Bandgap Devices in Power Electronics

3.1. The Working Principle of Wide Bandgap Devices in Power Electronics

Silicon based MOSFETs conduct electrons through the channel, controlling the width of the channel, and thus the number of electrons passing through it, by means of the voltage between the gate and the source. The three working regions are introduced from this principle: linear region, saturation region and velocity-saturation region. However, take Gallium Nitride as an example, it is different from common process to produce a silicon semiconductor by doping impurities to form a PN junction. Gallium Nitride semiconductors, which is defined as one kind of High Electron Mobility Transistors (HEMTs), are formed by two different semiconductors forming a heterojunction with PN-junction-like properties. And it can still be used in transistors with the property that the voltage difference between gate and source and between gate and drain can also control the device to enter the saturation, amplification, and cut-off states. In RF circuits, HEMTs tend to operate in an amplifying state. However, in power electronic circuits, in order to reduce the loss of the device, the HEMT tends to operate in the saturation and cut-off state, which is equivalent to the full conduction and switching off of the device. In circuits, this can be equated to switch closure and disconnection. GaN devices have lower on-resistance and smaller charging capacitance than SiC and Si devices. These characteristics allow GaN power devices to exceed 1MHz switching frequency.

Due to its wide bandgap, semiconductors can endure much higher avalanche breakdown voltage and temperature. Also, lower on state resistance and switch-off time can be obtained.

3.2. The Practical Application of Wide Bandgap Devices in Power Electronics

There are several types of semiconductors that use wide bandgap materials. One example is Infineon's F3L400R10W3S7F module [8]. It combines a Si IGBT with a SiC diode to achieve high power (950 V 400 A) for active three-level neutral point clamped (ANPC) inverter applications. The difference in forward characteristics makes SiC MOSFETs superior to SiC IGBTs, and the unipolar structure of MOSFETs offers linear (ohmic) characteristics, which are particularly beneficial for low load and partial load conditions.

A hybrid configuration using SiC MOSFETs and GaN FETs has been proposed for use in power management DC-DC converters for electric vehicles [9]. GaN FETs are the best candidate for hard-switching applications due to their low switching losses. However, commercially available GaN devices have a transverse structure that limits their power levels to 15 kW, while larger cars require 150 kW. A solution is to use a hybrid configuration where only the GaN conducts at low loads and the SiC and GaN share the current unequally at high loads. This would allow for the use of GaN FETs in high-power applications while maintaining the efficiency benefits of SiC MOSFETs.

A silicon carbide (SiC) MOSFET is placed in parallel with three silicon (Si) IGBTs in a 250-kW solar inverter to maintain both high efficiency and low cost [10]. SiC MOSFETs are employed for low to medium loads while three Si IGBTs are used for high loads. GaN devices have minimal switching losses, but their current-voltage ratings are even lower than those of SiC.

USB Power Delivery (USD-PD), a universal standard, facilitates power delivery to devices equipped with a USB-C port, including those with higher power requirements like hard drives, printers, laptops, and smartphones with large batteries. USB-PD chargers and adapters cater to a wide range of devices by dynamically adjusting the charging voltage and current to meet the precise power needs of the connected device. This versatility is enabled by the USB-PD protocol, enabling the power supply and power adapter to communicate and establish power delivery requirements. The power adapter then modifies its output voltage and current based on the specific demands of the connected device. Infineon's innovative CoolGaN™ technology redefines power transistor design by employing gallium nitride (GaN) transistors as opposed to traditional silicon MOSFETs [11]. This transition to GaN transistors yields several advantages over silicon MOSFETs. GaN transistors can withstand higher electric fields, allowing them to operate at higher switching frequencies, resulting in smaller, lighter, and more efficient chargers and adapters. GaN HEMTs (high electron mobility transistors) boast extremely low on-resistance, minimizing power losses and enhancing efficiency. GaN transistors exhibit lower capacitance compared to silicon MOSFETs, further reducing switching losses and boosting efficiency. By leveraging these advantages, GaN-based chargers and adapters can deliver higher power levels while maintaining compact form factors and lighter weights. Notably, smartphone companies like Oppo and Vivo have launched phone chargers capable of delivering over 200 watts of power while fitting comfortably in the palm of the hand.

4. The Future of Wide Bandgap Devices

4.1. Challenges of Wide Bandgap Devices

Wide bandgap devices have massive advantages. However, there are several challenges that slow down the development of making fully use of them. The progress of production can be more complicated and hence pricy compared to conventional silicon semiconductors [12]. This significant flaw makes users find it difficult to widely make use of wide bandgap materials. Also, the material required for producing the wide bandgap semiconductor is significantly higher than common. Defects of materials is a limitation on production and yields rate. And the common system is designed for systems using conventional semiconductors rather than wide bandgap devices. It is a challenge integrating wide bandgap semiconductors into existing systems or re-design a new structure. The aging and reliability are also crucial problem. Wide bandgap semiconductors are made for more harsh environments with higher restrictions like thermal and frequency limits. How to maintain its performance or declining its degradation of performance is critical. The sizing of wide bandgap semiconductors is another aspect

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needed to consider. Some wide bandgap semiconductors are already used under less important circumstances with small size, such as smartphone charging adaptors. However, how to reduce its size in applications with high frequency and power density, or further minimize its size in low power situations, is a challenging topic.

Diamond, despite its exceptional electrical properties, faces challenges in immediate implementation in high-power devices due to its intricate fabrication process. However, the potential for diamond to become a significant material for power devices within the next two to five decades remains strong. While transition materials like gallium nitride (GaN) and silicon carbide (SiC) are currently replacing silicon in many high-power applications, GaN boasts slightly superior intrinsic properties compared to SiC. However, it is practicality hampered by the lack of commercially available pure GaN wafers. Currently, GaN transistors must be grown on silicon carbide substrates, a process that adds to their overall cost and limits their manufacturability [13].

4.2. Future Employment of Wide Bandgap Devices

Wide bandgap semiconductors' capability of fitting in more complex and high-criterion applications has drawn massive attention. More and more individuals and organizations are working on making wide bandgap devices into multi-scenario and multi-functional use. The future employment of wide bandgap devices will spread over more required occasions. For using in electric vehicle charging, power electronics needed for electric vehicles charging slot can have higher efficiency hence less time to wait for charging with the use of wide bandgap semiconductors under high-frequency circumstances. And in the world of wireless communications systems, telecommunications are developing with much higher frequency. Wide bandgap devices' capability of enduring incredible high frequency meets the criteria. In common customers' appliances, adapters with higher power density and smaller size, which enables them to integrate more functionality. For medical and human health, the high-switching speed enables devices to sample data and images with high accuracy, which means higher possibility to detect symptoms for both doctors and patients.

5. Conclusion

This paper draws a conclusion about wide bandgap semiconductors' basic properties and using scenarios in power electronics. Also, this paper makes a vision for the future development. In a nutshell, wide bandgap semiconductors are commonly used as switches in power electronics applications. Due to the natural characteristics of wide bandgap materials, semiconductors can operate under more cruel circumstances like higher voltage, higher frequency, and higher temperature. However, not all kinds of wide bandgap materials can meet the criteria of practical use as theory, and there are some technical limits of the manufacturing procedure that make semiconductors cannot function ideally. Nowadays wide bandgap semiconductors' research and development is advancing at a rapid pace, fueling their application in power electronics. And at the same time, the increasing use of devices consisting of wide bandgap materials in power electronics is providing direction and guidance for their manufacturing. The existing difficulties are going to be solved and the future of wide bandgap devices are really promising.

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