A Comprehensive Review of Wide Band-Gap Semiconductors Technology

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Abstract

Power electronic converters use semiconductors to satisfy the needs of different applications. Nowadays, these semiconductors are mainly based on Silicon (Si), which can be processed virtually without defects. However, the limits of Si are being reached and in consequence, Si based semiconductors have limited voltage blocking capability, limited heat transfer capability, limited efficiency and maximum junction temperature. Silicon carbide (SiC) and gallium nitride (GaN) are typical representative of the wide band-gap semiconductor material, which is also known as third-generation semiconductor materials. Compared with the conventional semiconductor silicon (Si) or gallium arsenide (GaAs), wide band-gap semiconductor has the wide band gap, high saturated drift velocity, high critical breakdown field and other advantages; it is a highly desirable semiconductor material applied under the case of high-power, high-temperature, high-frequency, anti-radiation environment. These advantages of wide band-gap devices make them a hot spot of semiconductor technology research in various countries. This article present the review of literature of wide band semiconductor, focusing on the recent developments of the wide band-gap technology and summed up the facing challenge of the wide band-gap technology.

Keyword: Wide-bandgap (WBG), Silicon Carbide (SiC), Gallium-Nitride (GaN), Inverter, MOSFET, High Temperature.

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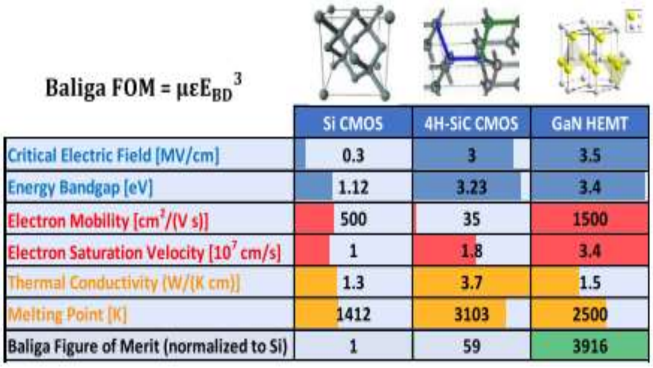
1. Introduction

As the demand for electric vehicles increases day by day, the need for dependable power electronic systems has grown for electric energy processing and conversion. The semiconductors that we are currently relying on will face a shortage in the upcoming years. Over the past few years, the requirement for smaller and more energy-efficient devices has been on the rise. Traditional semiconductors face multiple limitations when it comes to effectiveness in the performance of the circuit: this leads to a rise in wide-bandgap semiconductor research.

Technologies using wide-bandgap semiconductors are serving all the needs that are required today by the industry. As the name suggests, they have a larger bandgap due to which various electronic devices can operate at high voltages, temperatures, and frequencies. Silicon Carbide (SiC) and Gallium Nitride (GaN) are recently introduced wide-bandgap semiconductors which have the advantage of more power efficiency, reduced size and weight, and also result in a lower overall cost. Therefore, SiC and GaN are set to replace silicon-made devices as they have some limitations [1].

SiC has proved to have higher output power applications, which can be very useful in the field of electric vehicles (EVs), and, thereby, can be widely used for industrial automation. GaN comes with a higher switching frequency and lower power consumption. As compared to silicon, GaN has higher electron mobility, which enables the electrons to move quickly when passing through a semiconductor [2].

Wide-bandgap materials have a 3eV+ wide-bandgap due to which it becomes an important property to execute high voltage operations. Mobility and saturation velocity are suitable for high switching frequencies in the 2D channel of a Field-Effect Transistor (FET). One of the drawbacks of these specifications for SiC is that, during interfacing of SiC, the mobility is reduced. In GaN, 2D mobility is made possible as it comes with a high density of 2D electron gas while interfacing and modulation doping using its piezoelectric properties. There are various advantages of GaN FETs, like higher operating frequencies, better thermal conductivity, higher melting point, etc.[3].



Baliga FOM = $\mu\varepsilon E_{BD}^3$

	Si CMOS	4H-SiC CMOS	GaN HEMT
Critical Electric Field [MV/cm]	0.3	3	3.5
Energy Bandgap [eV]	1.12	3.23	3.4
Electron Mobility [$cm^2/(V\ s)$]	500	35	1500
Electron Saturation Velocity [10^7 cm/s]	1	1.8	3.4
Thermal Conductivity (W/(K cm))	1.3	3.7	1.5
Melting Point [K]	1412	3103	2500
Baliga Figure of Merit (normalized to Si)	1	59	3916

Figure 1: Comparative analysis of Semiconductor materials

2. Wide-Bandgap Technologies

The essential properties of the WBG materials can be summarized into the figures of merit (FOM). The study of novel semiconductor devices like Silicon super junction MOSFETs, SiC MOSFETs, and GaN FETs manufactured after 2015 is very useful for evaluating the maturity of the devices and figuring out the areas needed for advancement. For example, the parameters related to high voltage operations and resistive power losses are captured by the Baliga FOM (BFOM). This is a normalized breakdown voltage at on-state resistance parity for a unipolar device based on 1D electrostatics. BFOM is proportional to carrier mobility and is also relevant for the operation of unipolar devices such as MOSFETs and High-Electron Mobility Transistors (HEMTs) [4].

Wide-bandgap FETs
SiC MOSFETs are divided into two structures namely –

1. Planar
2. Trench

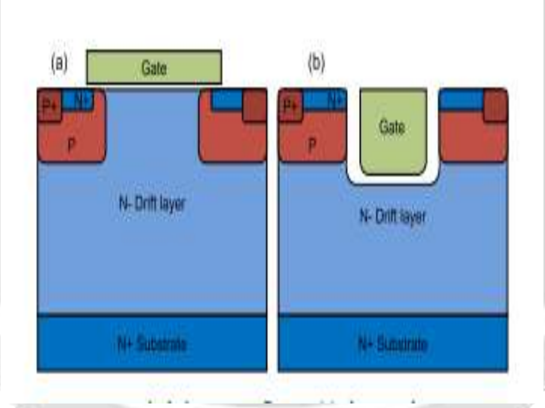


Figure 2: Planar (a) Trench(b)

High interface trap density causes low mobility, which limits the $R_{ds(on)}$. $R_{ds(on)}$ is on-resistance which means that it is the resistance between Drain and Source of a MOSFET. If the value of $R_{ds(on)}$ is small, then it indicates that the power loss is less. SiC MOSFETs have a range of 1.2KV- 6.5KV, with a breakdown voltage of 15kv. The $R_{ds(on)}$ is too high for using the SiC MOSFET for application purposes, so if we enhance the channel mobility, practically the problem can be solved.

Comparing the advantages and disadvantages of Silicon (Si) with Silicon Carbide (SiC) and Gallium Nitride (GaN)

	Si	SiC	GaN
Circuit topology	CMOS	CMOS	nFET
Maturity			
Main Selling Points	• Maturity • Cost per Performance • Reliability • Design Expertise	•High Temperature (300 C, JFET up to 500 C) •High Voltage (up to 10 KV)	• High switching frequency • Total system volume • Lateral devices suitable to monolithic integration
Main barriers to adoption	• Default • Si IGBT have 6.5 KV max BV	•Low mobility in the channel •High density of interface traps	• No pFET • No modulation doping • Poor contacts • Poor hole mobility • Large surface for high BV

Figure 3: Comparison between Si, SiC, and GaN

GaN's limitations

Despite having various advantages, there are also some reliability-based limitations while using GaN. These limitations can be eliminated once the fabrication process of GaN becomes more advanced [5].

Some of the limitations include:-

1. **Degradation of dynamic resistance:** When GaN is under high switching operation, the semi-ON condition is caused by the high drain voltage and current, which impacts the performance of the circuit. Due to this, the trapping of negative charges takes place. According to studies, the degradation is due to the joint effect of surface and buffer layer charge trapping.
2. **Threshold voltage instability of pGaN HFETs:** It is a severe problem in pGaN HFETs. The nature of the ohmic gate defines the instability of the threshold voltage.

3. Market Research of SiC and GaN

Wide-Bandgap semiconductors are rapidly increasing or expanding in the industry but due to technological barriers, they are limited to niches. GaN devices have a total annual revenue of 0.1% of the global power semiconductor market. According to future market predictions, there will be an increase in annual growth rate by 35% to 75% in the next 5 years. Most of the revenue can be pushed by the low-end market, consumer products including fast chargers, displays, and data centres. WBG Semiconductors can also be used as SiC inverters for the PV systems, GaN and SiC rectifiers, DC/DC converters for electric vehicle ultra-fast chargers. GaN and SiC have the potential to enhance the performance of power electronics and to get more effective outputs than that of traditional silicon devices. Considering the limitations of the WBG SiC and GaN, there's much more area for improvement as compared to silicon devices and the required improvement can be achieved only when the technology is enhanced [5]. Compared to traditional MOSFETs, WBG materials are much more economical. With improvements in fabrication technology, limitations of SiC and GaN-based MOSFETs will impulsively get eliminated creating more advantages, and a market for WBG semiconductors will rapidly see a potential increase, hence creating a replacement for the existing silicon-made devices.

4. Review of Literature

Amit Kumar et al. (2022) Power electronic systems have a great impact on modern society. Their applications target a more sustainable future by minimizing the negative impacts of industrialization on the environment, such as global warming effects and greenhouse gas emission. Power devices based on wide band gap (WBG) material have the potential to deliver a paradigm shift in regard to energy efficiency and working with respect to the devices based on mature silicon (Si). Gallium nitride (GaN) and silicon carbide (SiC) have been treated as one of the most promising WBG materials that allow the performance limits of matured Si switching devices to be significantly exceeded. WBG-based power devices enable fast switching with lower power losses at higher switching frequency and hence, allow the development of high power density and high efficiency power converters [6].

Millán and Godignon (2013) It is worldwide accepted that a real breakthrough in Power Electronics mainly comes Wide Band Gap (WBG) semiconductor devices. WBG semiconductors such as SiC, GaN, and diamond show superior material properties, which allow operation at high-switching speed, high-voltage and hightemperature. These unique performances provide a qualitative change in their application to energy processing. From energy generation to the end-user, the electric energy undergoes a number of conversions. Which are currently highly inefficient to the point that it is estimated that only 20% of the whole energy involved in energy generation reaches the end-user. WGB semiconductors increase the conversion efficiency thanks to their outstanding material properties. The recent progress in the development of high-voltage WBG power semiconductor devices, especially SiC and GaN, is reviewed [7].

Kizilyalli et al. (2018) The U.S. Department of Energy's Advanced Research Project Agency for Energy (ARPA-E) was established in 2009 to fund creative, out-of-the-box, transformational energy technologies that are too early for private-sector investment at make-or break points in their technology development cycle. Development of advanced power electronics with unprecedented functionality, efficiency, reliability, and reduced form factor are required in an increasingly electrified world economy. Fast switching power semiconductor devices are the key to increasing the efficiency and reducing the size of power electronic systems. Recent advances in wide band-gap (WBG) semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN) are enabling a new generation of power semiconductor devices that far exceed the performance of silicon-based devices. Past ARPA-E programs (ADEPT, Solar ADEPT, and SWITCHES) have enabled innovations throughout the power electronics value chain, especially in the area of WBG semiconductors. The two recently launched programs by ARPA-E (CIRCUITS and PNDIODES) continue to investigate the use of WBG semiconductors in power electronics. From materials and devices to modules and circuits to application-ready systems integration, ARPA-E projects have demonstrated the potential of WBG semiconductors to lower the cost of high-efficiency power electronics to enable broad adoption in energy applications [8].

Setera and Christou (2022) The role of crystal defects in wide bandgap semiconductors and dielectrics under extreme environments (high temperature, high electric and magnetic fields, intense radiation, and mechanical stresses) found in power electronics is reviewed. Understanding defects requires real-time in situ material characterization during material synthesis and when the material is subjected to extreme environmental stress. Wide bandgap semiconductor devices are reviewed from the point of view of the role of defects and their impact on performance. It is shown that the reduction of defects represents a fundamental breakthrough that will enable wide bandgap (WBG) semiconductors to reach full potential. The main emphasis of the present review is to understand defect dynamics in WBG semiconductor bulk and at interfaces during the material synthesis and when subjected to extreme environments. High-brightness X-rays from synchrotron sources and advanced electron microscopy techniques are used for atomic-level material probing to understand and optimize the genesis and movement of crystal defects during material synthesis and extreme environmental stress. Strongly linked multi-scale modeling provides a deeper understanding of defect formation and defect dynamics in extreme environments [9].

Krishna Shenai (2014) Power switching devices made from wide bandgap (WBG) semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN) have the potential to make transformative impact on electricity infrastructure. However, limited availability, high cost, unproven application-level field-reliability, inaccurate and incomplete datasheets from the manufacturers, and most importantly - lack of trust and true collaboration among the WBG supply chain industries - are severely hindering the large-scale commercialization of WBG power conversion technology. Although SiC power diodes and power MOSFETs are commercially available for voltage ratings up to 1,700 volts from a couple of manufacturers, a careful review of the published literature and commercial product datasheets suggests that performance and reliability of these devices may be severely compromised compared to silicon power devices. For example, limited reported data available for dv/dt, avalanche, and safe-operating area (SOA) parameters of SiC power diodes and MOSFETs are inferior to silicon power devices with identical ratings. This paper presents a simple physics-based analysis of power-handling capability of WBG power devices, and explains the possible causes of limited performance and reliability of SiC power devices [10].

Yifei Wang et al. (2022) the effects of defects and impurities on the material properties of Ga_2O_3 are mainly discussed. Considering that β-Ga_2O_3 is the most stable and the most studied currently, it is the main focus of this review. Firstly, the intrinsic properties (*e.g.*, electronic, absorption, thermal and mechanical properties) of β-Ga_2O_3 are introduced, and then the influence of impurities (*e.g.*, dopants and passivators) and defects on the electronic properties of β-Ga_2O_3 is discussed emphatically. Besides, the other properties (*e.g.*, luminescence, magnetic, and piezoelectric properties) of β-Ga_2O_3 modulated by defects and impurities are also briefly discussed. Meanwhile, some new research directions are also worth exploring. These problems and potential directions are summarized and discussed in the last section [11].

Giuseppe Iannaccone et al, (2021) expansion of the electric vehicle market is driving the request for efficient and reliable power electronic systems for electric energy conversion and processing. The efficiency, size, and cost of a power system is strongly related to the performance of power semiconductor devices, where massive industrial investments and intense research efforts are being devoted to new wide bandgap (WBG) semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN). The electrical and thermal properties of SiC and GaN enable the fabrication of semiconductor power devices with performance well beyond the limits of silicon. However, a massive migration of the power electronics industry towards WBG materials can be obtained only once the corresponding fabrication technology reaches a sufficient maturity and a competitive cos. They present a perspective of power electronics based on WBG semiconductors, from fundamental material characteristics of SiC and GaN to their potential impacts on the power semiconductor device market. Some application cases are also presented, with specific benchmarks against a corresponding implementation realized with silicon devices, focusing on both achievable performance and system cost [12].

S. Siva Subramanian et al. (2021) Improvements in the material characteristics of bandgap semiconductors allow the use of high-temperature, high-voltage, and fast switch rates in power devices. Another good reason for creating new Si power converter devices is that previous models perform poorly. (e implementation of novel power electronic converters means high energy efficiency but a more logical use of electricity. At this moment, titanium dioxide and gallium nitride are the most prospective semiconductor materials because of their great features, established technology, and enough supply of raw components. (is study is focused on providing an in-depth look at recent developments in manufacturing Si-C- and high-powered electronic components and showcasing the whole scope of the newly developing product generation [13].

5. Facing Challenge of Wide Bandgap Technology

5.1 Material immature or defective

SiC single crystal material defect exists, then reduce and eliminate the defect density, and the increase of single wafer size have become focuses of research. In recent years, great progress has been made in the respect of reduction and eradication of fatal flaw microtubule density, which result the SiC power semiconductor performance and reliability decrease; Cree Company began to supply 4 inches SiC single wafer of Zero Micropipes density in 2007. GaN material is immature, material defects results the critical breakdown field decline, Buffer substrate leakage of electricity is one of the main reasons of GaN power devices cannot reach the material theoretical limit [14].

5.2 Reliability issues

Two major technical difficulties of SiC devices have not been completely broken through: low inversion layer channel mobility and gate oxide reliability under high temperature and high electric field. Through a special gate oxidation process, SiC / SiO_2 interface defects can be eliminated to improve the inversion layer channel mobility. For SiC BJT power devices, now an urgent need to address is the current gain degradation. The reasons of instability caused by the current gain are still unclear; one reason possibly is due to the stacking fault caused the epitaxial base region. Reliability issues exist in GaN device; trap, material defects, surface treatment and passivation layer protection, Buffer substrate leakage, degradation of Schottky gate metal under high voltage and high current and high field, insulated gate dielectric and surface charge and other issues impact the GaN device reliability [15].

5.3 Packaging issues

There are packaging problems in high-temperature, high power SiC, GaN device. When SiC, GaN materials and processes problems are basically solved, Reliability issues of the device package will rise as the main factor impacting the high temperature high-power SiC, GaN device performance. Especially GaN, with equal level of power density of SiC, but the thermal conductivity is lower than SiC; thus it exacerbates the problem of thermal spreading of GaN device, and puts forward a more serious challenge for high power GaN device package [16].

6. Conclusion

In this paper, a review of SiC and GaN based power devices has been shown. It can be concluded that standard converter design guidelines can be applied but the faster switching behavior of these devices requires a more comprehensive understanding of the effects of parasitic elements. These devices are prone to EMI problems, voltage ringing and overshoots since their fast switching dynamics excite resonant circuits comprising leakage inductances and parasitic capacitances. To reduce these problems, decoupling capacitors with low Equivalent Series Inductance (ESL) and layouts with minimum leakage inductances are mandatory. A number of wide band-gap semiconductor technology development programs implemented in these countries will make the wide band-gap semiconductor technology research continue to rise to new levels, so that a variety of wide band-gap semiconductor devices become satellite communications, high-speed computers, precision guided, early warning and detection, intelligence and reconnaissance, electronic warfare, intelligent fire control systems and other military equipment's necessary and important components. Finally, in order to exploit the high junction temperature operation capability of WBG devices, it is mandatory the operation capability of packages, other surrounding auxiliary components and power devices at high temperatures.

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