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Posted Date: 25 November 2024

doi: 10.20944/preprints202411.1905.v1

Keywords: Sustainability; Wide-Bandgap Semiconductors; Epitaxial Growth Techniques; Manufacturing

Review

Sustainable Manufacturing and Applications of Wide-Bandgap Semiconductors

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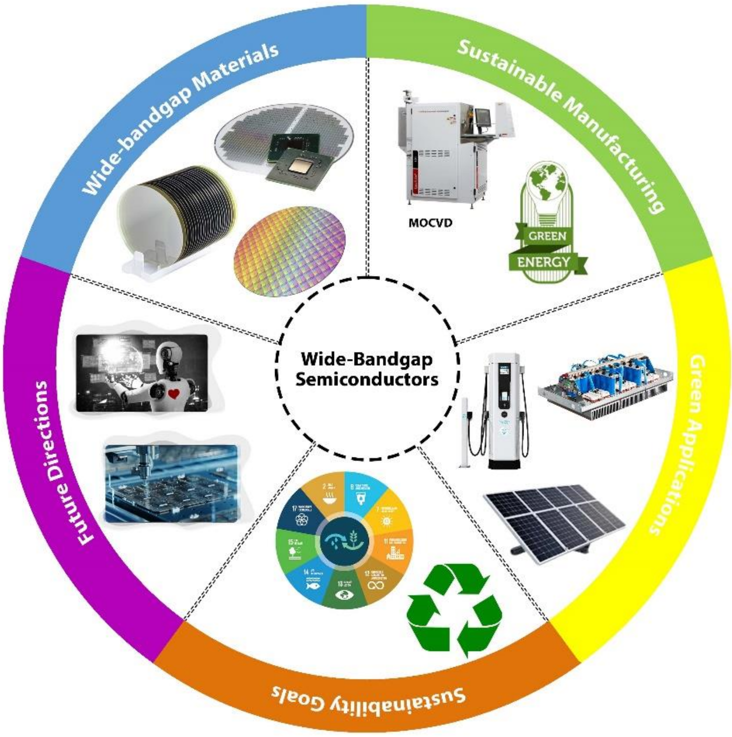
Highlights

- SiC and GaN exhibit superior thermal stability in high-power semiconductor devices.
- Sustainable WBG manufacturing reduces toxic byproducts and energy consumption.
- Low-energy epitaxial growth minimizes environmental impact during material processing.
- Recycling processes for SiC and GaN enable reduced semiconductor waste and cost.
- Ultrawide-bandgap materials face challenges in scalability and environmental sustainability.

Abstract: Wide-bandgap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) have become pivotal in high-power, high-frequency, and high-temperature applications. Their superior properties, including higher thermal conductivity, breakdown voltage, and energy efficiency, make them essential for advanced technologies like electric vehicles, renewable energy systems, and 5G infrastructure. However, their production processes are resource-intensive and pose significant environmental challenges. This review explores recent innovations in sustainable WBG manufacturing, focusing on low-energy epitaxial growth techniques, recycling of semiconductor materials, and efforts to reduce toxic byproducts. It also highlights the role of WBG materials in driving next-generation electronic systems and addresses the environmental concerns associated with scaling these materials for widespread use. The potential of Ultrawide-Bandgap (UWBG) materials for even more extreme applications is discussed, underscoring the need for continued innovation in sustainable practices to ensure the long-term viability of WBG technologies.

Graphical Abstract



Keywords: sustainability; wide-bandgap semiconductors; epitaxial growth techniques; manufacturing

1. Introduction

Wide-Bandgap (WBG) semiconductors like silicon carbide (SiC) and gallium nitride (GaN) are gaining recognition as enablers of sustainable technology innovations. Their superior properties in electrical and thermal performances enhance their indispensability in high-power, high-frequency, and high-temperature applications [1–3]. As industries engage in efforts to achieve global sustainability goals, WBG semiconductors offer the possibility to significantly improve energy efficiency in industries such as renewable energy, electric vehicles, consumer electronics and telecommunication [3]. However, while WBG materials offer clear advantages in performance and energy conservation, their production processes pose significant environmental challenges creating a paradox between their technological potential and their environmental impact. Addressing this tension is crucial as the world looks toward WBG semiconductors as a means of achieving both technological innovation and sustainability goals.

One of the defining characteristics of WBG semiconductors is their wider bandgap compared to traditional silicon-based semiconductors (Figure 1(a)). Their wider bandgap allows these materials to support higher voltages, higher frequencies, and higher temperatures, without the efficiency losses that are typical in silicon-based devices [4,5]. SiC and GaN semiconductors exhibit higher breakdown field strengths (Figure 1(b)), enhanced electron mobility, and better thermal conductivity than silicon, making them ideal for demanding applications where efficiency and performance under extreme conditions are critical [6]. Consequently, WBG semiconductors are thus better suited to power conversion systems in renewable energy infrastructure, electric vehicles (EVs), and next-generation power grids, where higher power density and greater energy efficiency are paramount [7,8].

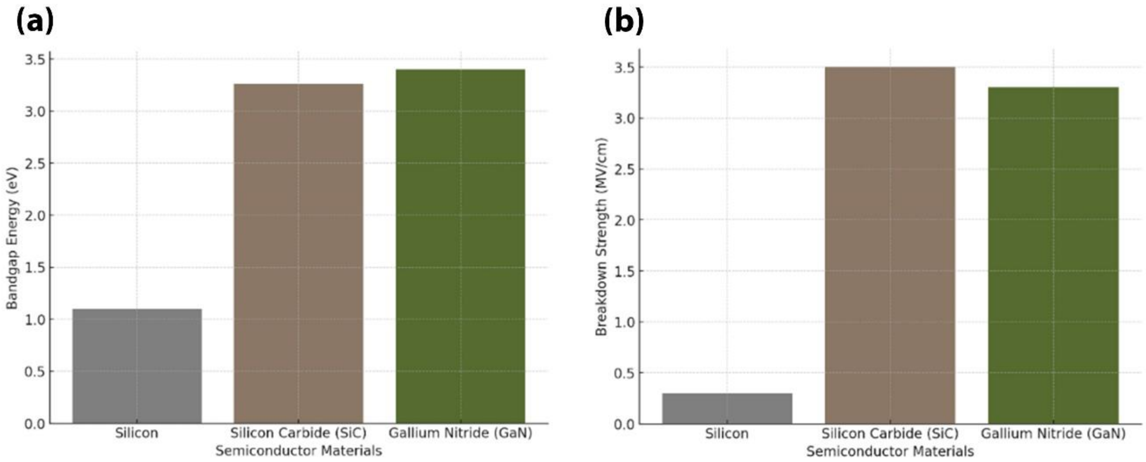


Figure 1. (a) Bandgap Energy Comparison of Semiconductor Materials (Silicon, SiC, GaN) (b) Breakdown Strength Comparison of Semiconductor Materials (Silicon, SiC, GaN).

The transition from silicon to Wide-Bandgap (WBG) semiconductors particularly Gallium Nitride (GaN) and Silicon Carbide (SiC), represents a significant advancement in power electronics mainly in applications like electric vehicles (EVs) and renewable energy systems. WBG devices possess a number of superior properties: high switching frequencies, reduced conduction losses and compact designs-resulting in enhanced efficiency in power conversion systems. For instance, GaN-based inverters showed peak efficiencies as high as 97.2%, significantly outperforming their traditional silicon solutions [7]. In EVs, the use of WBG semiconductors allows for improved battery utilization, resulting in longer driving ranges and faster charging times [2]. Furthermore, in renewable energy applications, WBG devices contribute to more efficient solar inverters and wind turbine converters, thereby increasing energy yield and minimizing the carbon footprint of power generation [9,10]. This transition allows significant strides in technological performance and contributes to global sustainability by saving energy and reducing greenhouse gas emissions [11].

Despite the enormous advantages coming from WBG semiconductors, the production processes involved are extremely resource and energy-intensive and raise environmental concerns. The production of SiC wafers, for instance, is characterized by high manufacturing energy demands, contributing to a substantial global warming potential (GWP) [12]. Additionally, epitaxial growth techniques, such as chemical vapor deposition (CVD), are required for high-quality WBG wafers to operate at elevated temperatures further increasing energy consumption and greenhouse gas emissions [4,13]. While WBG devices demonstrate superior performance, the environmental impact of their production processes including a higher carbon footprint compared to traditional silicon manufacturing, necessitates a careful evaluation of sustainability practices within the semiconductor industry [12,14]. Moreover, the extraction and processing of raw materials for WBG semiconductors pose ecological risks. SiC production is energy-intensive, contributing to high global warming potential due to the manufacturing energy required for SiC wafers. GaN relies on gallium, often sourced as a byproduct of aluminum and zinc mining which can lead to habitat destruction and pollution in poorly regulated mining regions [6,7,12]. As the demand for WBG semiconductors increases, the pressure on these finite resources will intensify, exacerbating environmental impacts [15]. Furthermore, the supply chain for these materials is geographically concentrated primarily in regions like China (Figure 2), which controls a significant portion of the global supply [16,17]. This concentration creates potential supply bottlenecks and raises concerns about the long-term sustainability of WBG semiconductor production, necessitating a re-evaluation of mining practices and resource management strategies to mitigate ecological damage.

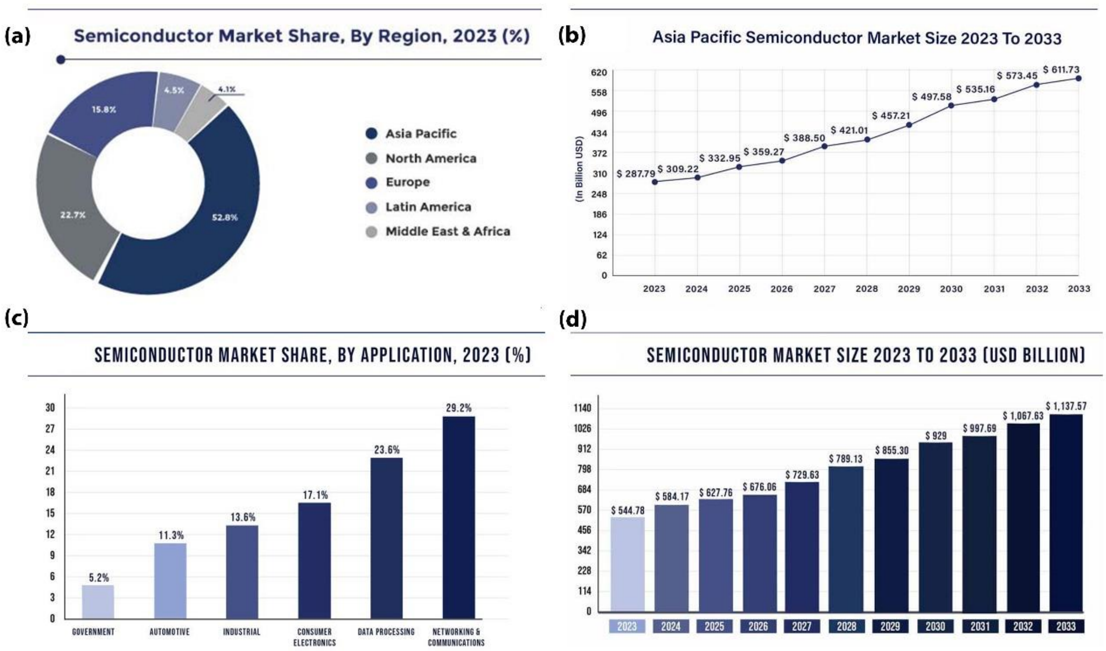


Figure 2. (a) Semiconductor Market Share by Region in 2023 (%). (b) Projected Semiconductor Market Size in the Asia Pacific Region from 2023 to 2033 (USD Billion). (c) Semiconductor Market Share by Application in 2023 (%). (d) Projected Global Semiconductor Market Size from 2023 to 2033 (USD Billion). Source: Precedence Research [18].

The environmental challenges associated with WBG semiconductors extend beyond raw material extraction and energy consumption during manufacturing. The lifecycle of Wide-Bandgap (WBG) semiconductors indeed presents significant environmental challenges, particularly concerning their end-of-life disposal. The materials used in WBG devices, such as gallium and silicon carbide, are often difficult to recycle, leading to substantial waste generation and resource loss [19]. The improper management of electronic waste (e-waste) exacerbates pollution and poses health risks, as hazardous substances can leach into the environment [20]. The current methodologies of recycling, such as mechanical and hydrometallurgical processes, are losing their economic and technological viability toward the efficient recovery of valuable material from e-waste [19]. Furthermore, the lack of robust regulatory frameworks and public awareness contributes to the challenges of managing e-waste sustainably [21]. Addressing these issues is crucial for minimizing the environmental footprint of WBG semiconductors and promoting sustainable resource management in the face of growing electronic waste concerns.

To reconcile the benefits of Wide-Bandgap (WBG) semiconductors with their environmental impact, significant efforts are being directed toward more environmentally benign production methods and lifecycle management strategies. Research emphasizes the development of energy-efficient manufacturing processes, such as optimizing epitaxial growth techniques to minimize energy consumption during WBG wafer production, which aligns with the broader goal of reducing the carbon footprint in manufacturing [22]. Sourcing of materials has to be sustainable; the semiconductor foundry industry is increasingly focusing on the minimization of hazardous waste and resource efficiency, which can also be applied to WBG materials [14]. More than that, innovations in recycling technologies are being explored to recover rare materials used in WBG production, thereby mitigating the environmental impacts associated with raw material extraction and promoting a circular economy [23]. These universal efforts are turning out to be indispensable in improving the sustainability of WBG semiconductors facing ever-increasing demand for advanced electronic applications [24].

The integration of sustainability practices in the design and production of Wide-Bandgap (WBG) semiconductor devices is crucial for minimizing environmental impacts. Advanced manufacturing techniques, such as chemical vapor deposition (CVD) at lower temperatures and molecular beam epitaxy (MBE), can significantly reduce energy consumption during production, aligning with the semiconductor industry's goal to lower greenhouse gas emissions [22]. Adopting a circular economy approach by focusing on material efficiency and waste reduction can also enhance sustainability in semiconductor manufacturing. Extending the lifespan of WBG devices is another vital strategy, as it reduces the frequency of replacements and the associated electronic waste [23,25].

The semiconductor industry can enhance its operational efficiency and sustainability by implementing various green supply chain management (GSCM) practices. For instance, adopting advanced technologies such as telematics and data analytics can optimize transportation routes, thereby reducing fuel consumption and emissions during distribution processes [26]. Fostering collaboration with suppliers and logistics providers can facilitate the sharing of best practices and joint initiatives, which is crucial for effective GSCM implementation [26]. Also, integrating sustainability into supply chain strategies can improve brand reputation and customer loyalty while achieving cost savings [27]. The semiconductor sector can also benefit from establishing a structured green supply chain framework, similar to Lenovo's model, which emphasizes cooperation among supply chain partners to enhance sustainability and reduce governance costs [28]. By addressing technological risks and complexities through these practices, the industry can demonstrate a commitment to responsible production and consumption [29,30].

Despite these sustainability initiatives, several challenges are persistent in the manufacturing and life-cycle management of WBG semiconductors. One of the key hurdles is the high cost associated with the production of WBG materials, particularly in comparison to traditional silicon-based semiconductors. The energy-intensive process in the case of WBG contributes to the higher costs, which may be a barrier to penetration into cost-sensitive industrial applications [14]. To address these challenges, the semiconductor industry must focus on innovations in manufacturing techniques and achieving economies of scale, as highlighted in the research on green supply chain adoption [29]. Integrating sustainability at product development can further increase the capability of the industry to go through cost reduction with improved environmental performance [31]. The need for sustainable engineering solutions is underscored by the broader challenges of balancing economic viability with environmental impact, as outlined in the Sustainable Development Goals [32]. Overcoming these hurdles is essential for the global viability of WBG semiconductors in sustainable technologies.

Another challenge lies in the need for a more robust infrastructure to support the recycling and recovery of WBG materials. Wider utilization of WBG semiconductors requires better recycling technologies capable of reclaiming expensive materials from end-of-life devices. The automotive sector for instance, is increasingly focusing on circular economy principles, emphasizing the recovery of valuable materials from electronic components, including WBG devices, through innovative decision-making frameworks that enhance sustainability [23]. The recycling of lithium-ion batteries (LIBs), which may incorporate WBG materials, is gaining attention due to regulatory pressures and the need for efficient resource management [33]. The challenges of developing effective recycling technologies for WBG materials highlight the importance of collaboration among industry, government, and academia to create regulatory frameworks that incentivize recycling efforts [34]. The transition towards a circular economy requires comprehensive strategies that address the entire lifecycle of materials, ensuring that valuable resources are reclaimed and reused effectively [35,36].

This review provides an in-depth exploration of the innovations, sustainability practices, challenges, and future prospects of Wide-Bandgap (WBG) semiconductors. The first section analyzes recent advancements in WBG technologies, with a focus on their applications in high-power, high-efficiency industries, such as renewable energy systems and electric vehicles, where they are revolutionizing performance and efficiency. The second section delves into current sustainability initiatives aimed at mitigating the environmental impact of WBG semiconductor production, such as improving energy efficiency, minimizing material waste, and developing advanced recycling techniques. The third section addresses the specific challenges associated with WBG semiconductor production, ranging from raw material extraction to lifecycle management, and evaluates the

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industry's response to these environmental concerns. Finally, the review looks ahead to the future of WBG semiconductors, discussing their potential to drive sustainable technological innovation and outlining the strategic steps required to align their development with broader sustainability goals.

2. Semiconductor Fundamentals and Historical Development

2.1. Introduction to Semiconductors

Semiconductors are essential materials characterized by their electrical conductivity, which lies between that of conductors and insulators, making them vital for controlling electric current in electronic devices [37]. They are classified into intrinsic semiconductors, which are pure, and extrinsic semiconductors, which are doped with impurities to enhance conductivity [38]. Among the semiconductors, silicon is used extensively due to its high-temperature stability and effective doping capabilities, allowing for the creation of both p-type and n-type semiconductors [38,39]. This ability to be doped and integrated into complex circuits has been foundational for modern electronics, supporting the development of a wide range of devices, from computers to telecommunications systems [40]. The dominance of silicon underscores its central role in advancing various technological applications, highlighting its significance in the evolution of electronic technology [39,40].

2.2. The Shift to Wide-Bandgap (WBG) Semiconductors

The increasing demand for more efficient, reliable, and high-performance electronic systems has driven a transition from traditional silicon-based semiconductors to Wide-Bandgap (WBG) technologies. Wide-bandgap (WBG) semiconductors like Silicon Carbide (SiC) and Gallium Nitride (GaN) outperform Silicon (Si) by offering significantly larger bandgaps - around 3.3 eV for Silicon and 3.4 eV for GaN (Table 1, Figure 3). This enables WBG devices to operate at much higher voltages, temperatures, and frequencies while reducing energy losses and minimizing thermal degradation [41].

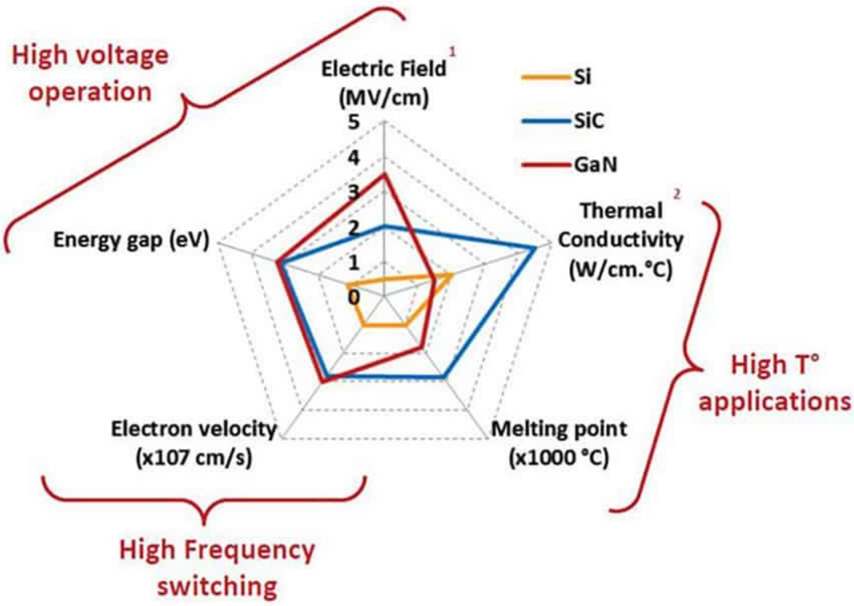

Figure 3. Material Properties of WBG semiconductors (SiC, GaN) compared to Si presented in a spider chart.

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Table 1. Physical properties of Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN) [47].

Electrical Property	Si	4H-SiC	GaN
Bandgap energy (eV)	1.1	3.26	3.4
Thermal Conduction (W/cm.K)	1.5	3.7	1.3
Electron Mobility (Cm^2/V.s)	1300	900	900 - 2000
Saturation drift velocity	1×10^7	2×10^7	2.5×10^7

As industries such as electric vehicles, renewable energy systems, and aerospace demand greater efficiency and power density, the limitations of silicon devices—especially in terms of temperature tolerance and frequency—have become more apparent. SiC devices, for instance, maintain functionality at temperatures exceeding 200°C, while GaN excels in high-frequency applications, offering superior performance in power conversion and RF applications [5,41]. The higher thermal conductivity and breakdown voltages of WBG materials also ensure greater reliability in extreme conditions, reducing the need for additional cooling systems and enhancing long-term durability [41,42].

This transition to WBG technology represents a pivotal advancement in semiconductor design, fostering the development of more efficient and robust electronic systems. This transition is crucial for meeting the evolving needs of green technologies, electrified transportation, and next-generation power electronics [5,43].

2.3. Fundamental Properties of Wide-Bandgap (WBG) Semiconductors

With their inherent properties, WBG devices can function effectively at temperatures up to 300°C, far exceeding the 150°C limit of traditional silicon devices [2,41]. The superior material properties of WBG semiconductors, including high thermal conductivity and reduced conduction losses, enable them to be appropriate for demanding applications in electric vehicles, renewable energy systems, and aerospace.[7,9]. Their ability to switch at high frequencies while maintaining efficiency enhances the performance of power converters, which is crucial for the evolving needs of electrified transportation and green technologies [1,2].

Silicon carbide (SiC) exhibits a thermal conductivity of approximately 3.7 W/cmK, which is significantly higher than silicon's 1.5 W/cmK (Table 1, Figure 3), making SiC particularly advantageous for high-temperature applications such as electric vehicle powertrains due to its effective heat dissipation capabilities [41]. In contrast, gallium nitride (GaN) has a lower thermal conductivity of about 1.3 W/cmK; however, its superior electron mobility (Table 1) allows for enhanced efficiency in high-frequency switching applications, as utilized in 5G networks and radar systems [44]. The thermal management of GaN-based devices is critical, as self-heating effects can lead to performance degradation [44] Furthermore, the thermal conductivity of GaN can be influenced by structural properties, impurities, and layer thickness, which are essential considerations for optimizing device performance [45,46]. Thus, while SiC excels in thermal conductivity, GaN's high electron mobility makes it a strong candidate for specific high-frequency applications.

Silicon Carbide (SiC) and Gallium Nitride (GaN) significantly outperform traditional silicon in terms of breakdown voltage, with SiC capable of handling up to 1,700 V and GaN around 650 V, compared to silicon's maximum of about 400 V [41]. This enhanced voltage handling allows for more compact designs in power electronics, as fewer components are required to manage the same power load, thereby improving device efficiency and reliability [7]. High thermal conductivity and fast electron mobility are other superior material properties of WBG semiconductors contributing to their effectiveness in high-power applications. [2,9]. WBG devices are increasingly finding their applications in solar inverters, electric grids, and other applications that demand both compactness and high performance. This is essential for the evolving landscape of power electronics [11].

Gallium Nitride (GaN) exhibits remarkable efficiency in high-frequency applications due to their superior electron mobility of 2,000 cm^2/Vs (Table 1), which facilitates faster-switching speeds and minimizes energy losses during power conversion [2]. This characteristic is especially beneficial in renewable energy systems, where efficient power conversion is essential for maximizing energy output [9]. GaN's capability to operate at elevated frequencies allows for the integration of smaller passive components, resulting in lighter and more compact power electronic devices [7,48]. The reduced size of these components not only enhances the overall system efficiency but also contributes to the development of more space-efficient designs, which is critical in applications such as electric vehicles and renewable energy inverters [49]. Overall, the advantages of GaN in high-frequency applications underscore its pivotal role in advancing modern power electronics.

2.3. Historical Development of Wide-Bandgap (WBG) Semiconductors

The history of semiconductors is encapsulated by major discoveries, starting with Alessandro Volta, who, in 1782, coined the term "semiconductor," providing a name that would form the groundwork for other explorations to come (Figure 4) [50]. The photovoltaic effect, discovered by Alexandre-Edmond Becquerel in 1839, was pivotal for modern solar technology, culminating in Charles Fritts' creation of the first solar cell in 1883 using selenium (Figure 4) [51]. In the early 20th century, Sir John Ambrose Fleming was credited for pioneering the invention of the vacuum tube in 1904 (Figure 4). This was then followed by the discovery of the first commercial silicon transistor by John Bardeen and Walter Brattain in 1947 (Figure 4), establishing silicon as the dominant semiconductor material [39] However, by the 1990s, silicon's limitations in high-power and high-temperature applications prompted research into alternative materials like silicon carbide (SiC) and gallium nitride (GaN), recognized as Wide-Bandgap semiconductors [38,52]. This evolution reflects the ongoing quest for improved semiconductor performance and applications.

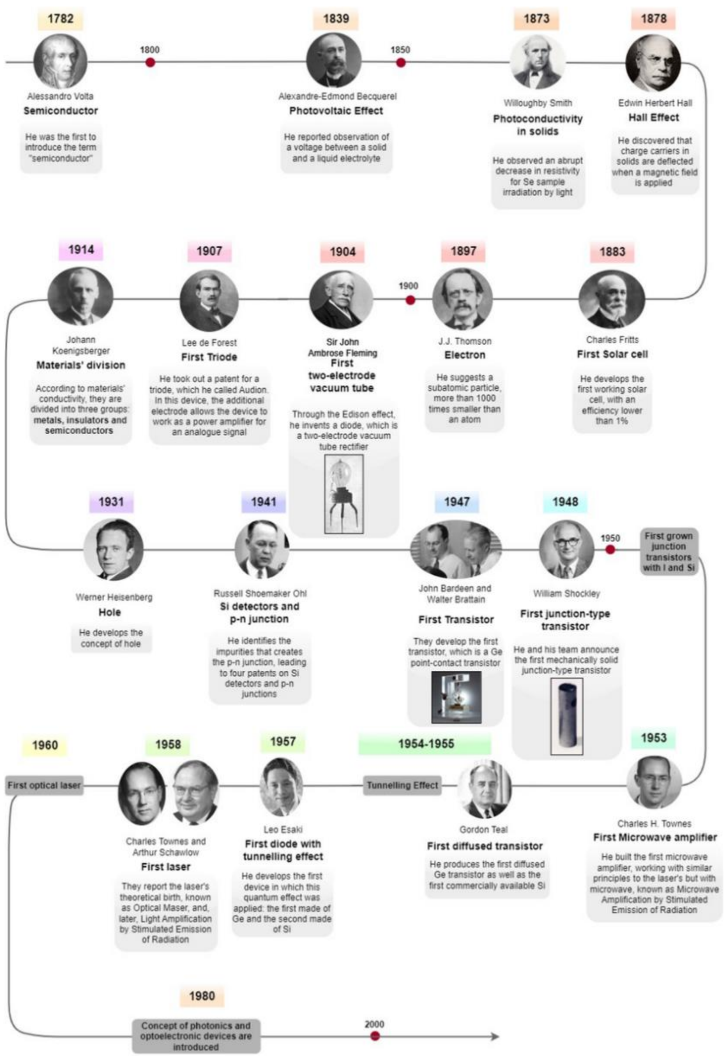

Figure 4. Timeline of the most important historical milestones throughout the last centuries [51].

Emergence of SiC and GaN

Silicon Carbide (SiC) power devices, developed in the 1990s, have significantly transformed the semiconductor industry by enabling high-temperature applications due to their exceptional properties, such as high thermal conductivity and electric field strength, making them ideal for power electronics in electric vehicles and renewable energy systems [53,54]. Concurrently, Gallium Nitride showed up in the early 2000s as a key material for high-frequency electronics: better breakdown voltage and switching speed compared to traditional silicon semiconductors, making it crucial for high-performance applications [41]. The advancements in Wide-Bandgap (WBG) materials like SiC and GaN not only enhance efficiency but also allow operation at higher voltages and temperatures, facilitating innovations in power management systems and contributing to sustainability efforts within the technology sector [55]. This evolution in semiconductor technology marks a pivotal shift, driving the development of more efficient and reliable power electronics.

Pivotal Technological Advancements

The Power Electronic Building Block (PEBB) program, initiated in 1994, significantly advanced Silicon Carbide (SiC) technology by focusing on reducing size, weight, and cost for military power electronics, which also benefited commercial sectors like electric vehicles [56]. SiC devices have shown remarkable capabilities, handling voltages up to 20 kV, making them ideal for applications in electric vehicle powertrains and energy storage systems [41]. Concurrently, Gallium Nitride (GaN) devices gained traction for their efficiency in power conversion, particularly in electric vehicles where

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compact and energy-efficient designs are essential [41]. By the mid-2000s, Wide-Bandgap (WBG) semiconductors, including SiC and GaN, demonstrated significant performance enhancements, with GaN devices achieving switching frequencies up to 2 MHz, which is beneficial for fast chargers and RF amplifiers [41,57]. This synergy between military and commercial applications has propelled the development of advanced power electronics technologies.

Impact on Modern Applications

The integration of Wide-Bandgap (WBG) semiconductors—most prominently Gallium Nitride and Silicon Carbide—has considerably modernized applications in contemporary electric vehicle and renewable energy sectors. These materials exhibit superior properties such as high electron mobility, high breakdown voltage, and excellent thermal conductivity, which enable more efficient and compact power management systems, thereby enhancing the vehicle's performance and range in EVs [7,41]. In renewable energy systems, SiC devices have notably improved the efficiency of photovoltaic inverters, minimizing energy losses and costs associated with solar energy conversion [2]. Furthermore, both GaN and SiC are pivotal in revolutionizing power supply systems by reducing energy losses during conversion processes, contributing to sustainability efforts aimed at lowering carbon footprints [58,59]. Emerging WBG materials like aluminum phosphide, diamond, and boron nitride also show promise due to their superior properties, such as high thermal conductivity and breakdown strength, which are essential for high-power applications in extreme environments [13]. Collectively, all these developments together contribute to the global efforts aimed at tackling modern energy-related problems and minimizing the carbon footprint [7,41].

Evolution Toward Sustainable Manufacturing

The transition to sustainable manufacturing is very crucial, especially in WBG semiconductor manufacturing, since the sector involves highly energy-intensive processes with environmentally toxic by-products. Conventionally, the manufacturing industry has faced severe impacts on the environment, arousing the need for development toward sustainability that would also corroborate green manufacturing principles. Strategies such as renewable energy integration, energy efficiency measures, and waste reduction are critical in mitigating ecological impacts and reducing carbon footprints [22,60]. Various technological innovations like the integration of Interne of all Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Robotics and automation have driven recent transitions to sustainable manufacturing, including smart manufacturing systems for optimization in resource use with minimal wastage [61], [62–64]. Despite the growing interest in Sustainable Product Development (SPD), the adoption of these practices remains limited, indicating a substantial opportunity for improvement in the industry [31]. Given the continuous demand for electronic devices, there is a further need to enhance the sustainability of the semiconductor manufacturing industry due to increased scrutiny and interest in environmental stewardship

Environmental Impact of Manufacturing

The manufacturing of Wide-Bandgap (WBG) semiconductors, particularly Silicon Carbide (SiC) and Gallium Nitride (GaN), is indeed resource-intensive and poses significant environmental challenges. The reliance on fossil fuels during production contributes to substantial carbon emissions, while the processes generate hazardous chemical byproducts that threaten air and water quality [49]. During the wafer fabrication process, significant emissions of non-methane hydrocarbons (NMHCs) occur, particularly from processes such as photolithography, which has the highest untreated emissions rates [65]. These NMHCs, including solvents like acetone and methanol, can contribute to air pollution and human toxicity [65]. As the demand for WBG devices grows, especially in sectors like electric vehicles and renewable energy systems, there is an urgent need to adopt cleaner and more efficient manufacturing methods to mitigate these impacts [9]. Furthermore, the lifecycle of WBG technology, from raw material supply to end-of-life disposal, necessitates a comprehensive approach to sustainability, emphasizing the importance of proper disposal of toxic substances [49].

Research into the environmental aspects of WBG materials is still emerging, highlighting the need for policymakers to develop informed strategies that promote sustainable practices within the semiconductor industry [49].

Current Innovations

Recent innovations in Wide-Bandgap (WBG) semiconductor manufacturing are significantly addressing environmental impacts through enhanced energy efficiency and waste reduction strategies. Advances in epitaxial growth techniques are optimizing energy use, thereby lowering greenhouse gas emissions associated with production processes, which is a crucial step in mitigating the environmental challenges of traditional manufacturing methods [24]. The semiconductor industry is increasingly adopting closed-loop recycling systems, allowing for the recovery and reuse of materials like silicon wafers. This practice not only conserves raw materials but also minimizes waste, preventing substantial amounts of semiconductor waste from entering landfills [14]. The integration of green chemistry principles is reducing the reliance on hazardous substances, leading to a decrease in toxic waste generation during production [22]. The green chemistry principles emphasize on the design of chemical products and processes that minimize or eliminate the use and generation of hazardous substances. For instance, the use of aliphatic amino acids as environmentally friendly corrosion inhibitors in Chemical Mechanical Planarization (CMP) slurries exemplifies this approach, replacing more toxic alternatives like benzotriazole (BTA) [24]. All these innovations together indeed represent a great leap forward toward greener semiconductor manufacturing—ensuring a healthier environment for production and rising to the call for global sustainability.

Integration of Industry 4.0 and Reconfigurable Technologies

The integration of Industry 4.0 technologies, such as Cyber-Physical Systems (CPS), the Internet of Things (IoT), and Artificial Intelligence (AI), is revolutionizing manufacturing processes by enhancing resource management and minimizing emissions, particularly in semiconductor production [66,67]. These intelligent manufacturing systems facilitate real-time data analysis and automation, allowing for adaptive manufacturing that can swiftly respond to changing market demands [68,69]. Reconfigurable technologies play a crucial role in this transformation, enabling manufacturers to fine-tune their processes dynamically, which not only boosts production efficiency but also significantly reduces waste and environmental impact [66,70]. By leveraging these advanced technologies, industries can achieve higher operational effectiveness and sustainability, positioning themselves competitively in the evolving digital landscape [67,68]

Toward a Circular Economy

The semiconductor industry is increasingly embracing circular economy principles to enhance sustainability by optimizing resource utilization and minimizing waste throughout the product lifecycle. This shift involves the integration of digital technologies such as IoT, AI, and blockchain, which improve visibility and traceability in supply chains, thereby facilitating the reuse and recycling of materials from raw material extraction to end-of-life disposal [64,71]. A structured framework for sustainable manufacturing is thus relevant to help organize the efforts of industry in the direction of resource conservation and address the complexities surrounding green supply chain management. [29]. The adoption of circular economy practices not only mitigates environmental impacts but also promotes economic benefits through innovative business models that prioritize waste reduction and resource efficiency [72,73]. As policymakers and industry leaders recognize these advantages, the momentum toward a more resilient and eco-friendlier semiconductor industry continues to grow [71].

3. WBG Semiconductor Manufacturing

3.1. GaN and SiC Semiconductor Manufacturing Route

GaN Manufacturing Route

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The manufacturing of gallium nitride (GaN) involves several critical steps to ensure that the layers are high-quality and suitable for advanced electronic applications. It begins with substrate preparation, where materials like sapphire, silicon, and silicon-on-insulator (SOI) are cleaned and patterned to create a defect-free surface for GaN growth [74]. Epitaxial growth is primarily achieved through Metal-Organic Chemical Vapor Deposition (MOCVD), where GaN is deposited from metal-organic precursors at elevated temperatures, often utilizing a buffer layer to enhance the quality of the film [59,75]. The growth process can be tailored to form structures such as AlGaN/GaN heterostructures, which are essential for high electron mobility transistors (HEMTs) [75]. Doping is performed via ion implantation techniques (e.g., magnesium for p-type conductivity), optimized to minimize damage and enhance ion activation [76]. Additionally, etching processes, including photoelectrochemical etching, are employed to create deep trench structures that improve heat dissipation and reduce parasitic capacitance. Finally, photolithography is used for pattern definition, followed by metal contact deposition, culminating in the dicing and packaging of the final devices for integration into electronic systems [59].

SiC Manufacturing Route

Silicon Carbide (SiC) substrates are primarily produced using the physical vapor transport (PVT) technique, which is essential for achieving high-quality single crystals due to the limitations of traditional melt-based methods [77,78]. Following substrate production, the wafers undergo polishing to ensure a smooth surface, which is critical for subsequent epitaxial growth using chemical vapor deposition (CVD) techniques that allow precise control over layer thickness and composition [77,79]. Doping is achieved through ion implantation or diffusion, with nitrogen for n-type and aluminum for p-type doping, necessitating careful control to maintain material integrity [80]. Reactive ion etching (RIE) is employed for patterning SiC wafers, ensuring minimal damage to the substrate [81]. Finally, photolithography is used for device fabrication, where metal contacts are deposited and annealed to ensure good electrical connectivity, followed by rigorous testing before packaging for applications in power converters and electric vehicles [77].

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3.2. Innovations in WBG Semiconductor Manufacturing

The growing demand for Wide-bandgap (WBG) semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), along with Ultrawide-Bandgap materials like gallium oxide (Ga_2O_3) necessitates a focus on sustainable manufacturing practices to mitigate energy consumption, manage toxic byproducts, and address resource depletion [43]. The challenges associated with doping these semiconductors, which can lead to inefficiencies and increased waste, further emphasize the need for innovative approaches in their production [82]. As the industry evolves, integrating sustainability into the development and manufacturing processes of WBG materials will be crucial for meeting both performance and environmental goals [5,42].

The concept of the circular economy has been increasingly applied in the field of semiconductors as a principle for better sustainability by recycling and reusing. Wafer reclaiming exemplifies this approach, where used silicon wafers are polished and reused, significantly reducing the demand for new silicon extraction and minimizing semiconductor waste disposal (Table 2) [23]. Recovery techniques for valuable materials like gallium and silicon from production byproducts are being integrated into manufacturing processes, allowing for the reuse of materials previously deemed waste [83]. This aligns with broader circular economy models that emphasize resource preservation and waste reduction, as seen in various industries, including minerals and metals, where similar recovery and recycling strategies are implemented [84]. Closed-loop manufacturing systems are also being explored to reintegrate production waste into the manufacturing cycle, thereby further decreasing the environmental footprint of semiconductor production (Table 2) [85]. Collectively, these practices contribute to achieving sustainable development goals and enhancing the overall efficiency of the semiconductor industry.

The transition toward sustainable Wide-Bandgap (WBG) semiconductor manufacturing is increasingly focused on reducing energy consumption during production, particularly in energy-intensive processes like Chemical Vapor Deposition (CVD) (Figure 5a). Innovations such as low-temperature/pressure CVD (Figure 5b, Table 2) and Atomic Layer Deposition (ALD) (Figure 5c) are emerging as energy-efficient alternatives, allowing for the production of high-quality films at significantly lower temperatures, thus minimizing energy usage [24]. Additionally, Molecular Beam Epitaxy (MBE) (Figure 5d) employs controlled, low-energy processes that enhance material quality while further reducing energy requirements [24]. The semiconductor foundry industry, which has historically faced challenges related to high energy and water consumption, is also exploring these advanced techniques to mitigate its environmental impact [14]. By integrating renewable energy sources (Table 2) and optimizing manufacturing processes, the industry can achieve substantial reductions in greenhouse gas emissions and waste generation, aligning with broader sustainability goals [22,86].

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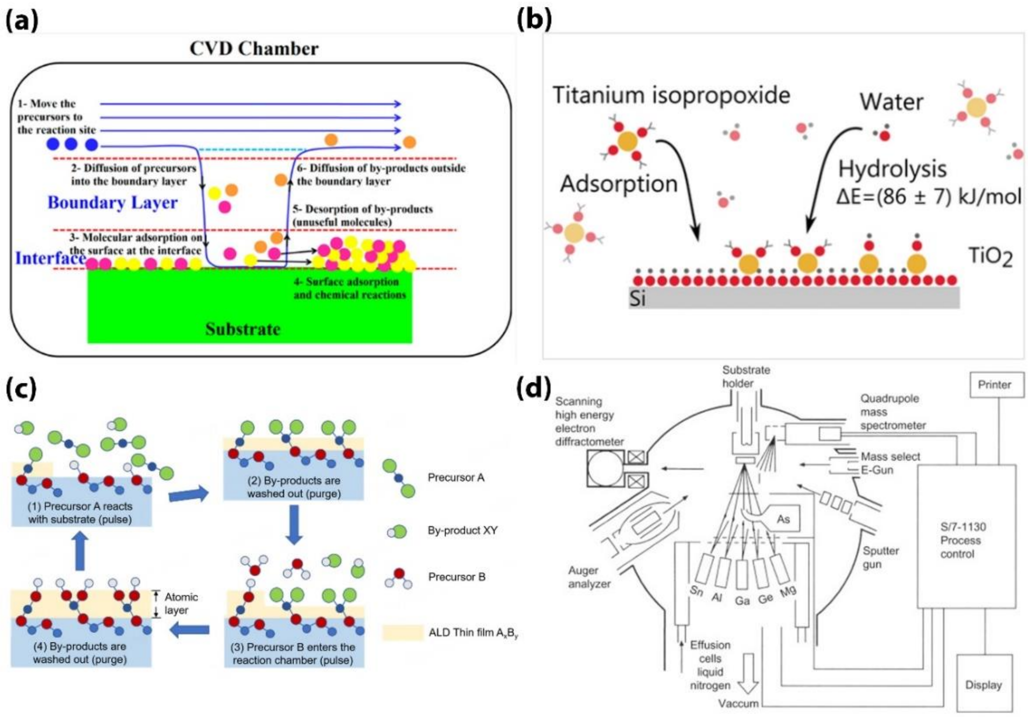

Figure 5. (a) Schematic of the main steps of the CVD process [87]. (b) Schematic Diagram of ALD type reaction to a high Vacuum Low-temperature CVD process [88]. (c) The reaction process of ALD [89]. (d) Typical MBE system [90].

The semiconductor industry faces significant environmental and health challenges due to the use of toxic chemicals like hydrogen fluoride (HF) in manufacturing processes. To address these concerns, there is a growing emphasis on green chemistry approaches aimed at reducing or eliminating hazardous substances (Table 2). Research is in progress to establish alternative chemical agents that could replace HF in such applications with minimum risk to health and the environment [24]. Innovative methods for capturing and recycling harmful byproducts are being implemented, allowing manufacturers to convert waste chemicals into reusable materials, thus preventing emissions and reducing reliance on toxic substances [91,92]. The adoption of less hazardous chemicals and stringent chemical management protocols is crucial for safeguarding worker health and ensuring compliance with environmental regulations [93]. These are methodologies and strategies that, in combination, contribute to a much more sustainable semiconductor manufacturing process and hence support the innovation required by the industry while addressing environmental sustainability. [14].

Advanced Industry 4.0 technologies, more so AI, machine learning, and digital twin integration, have manifold increased sustainability in WBG semiconductor manufacturing. AI-based manufacturing systems analyze large volumes of data to identify inefficiencies and optimize resource utilization, thereby reducing waste and energy consumption (Figure 6) [94,95]. Machine learning algorithms forecast equipment maintenance to avoid breakdowns and defective products, which further reduces material waste [96]. Digital twin technology creates virtual replicas of production processes, allowing manufacturers to simulate various scenarios and identify energy-efficient approaches, thus expediting the adoption of energy-saving techniques [96,97]. Reconfigurable manufacturing systems enable dynamic adaptation of production lines to meet changing demands, optimizing resource use and minimizing waste [98]. These technological advancements will help create a more sustainable manufacturing environment by helping improve efficiency and reducing environmental impact.

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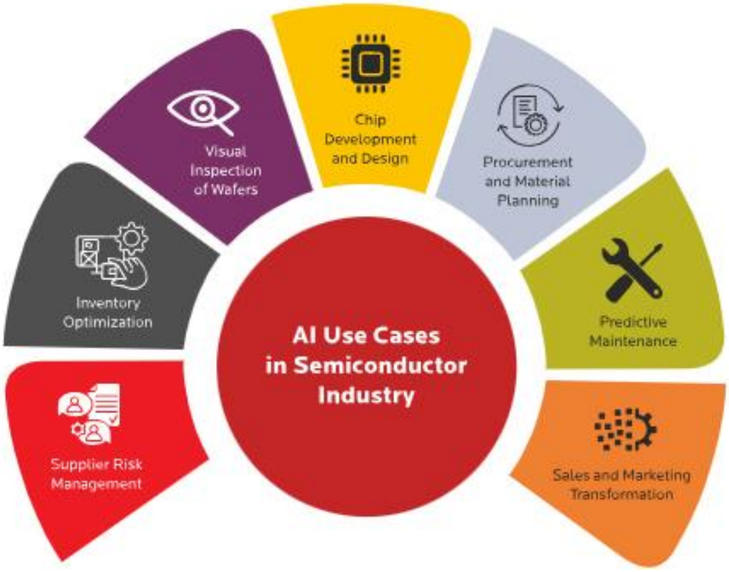

Figure 6. AI use cases in semiconductor industry. (Source: birlasoft [99]).

The semiconductor industry faces significant challenges in achieving sustainability, particularly concerning the sourcing of critical materials like gallium and silicon, often extracted from regions with inadequate environmental and labor regulations. This raises ethical concerns related to environmental degradation and human rights abuses [100]. To combat these issues, companies must implement robust traceability systems that ensure responsible sourcing of raw materials, as some manufacturers have begun to adopt tracking systems to enhance transparency and confirm ethical sourcing [101]. However, widespread adoption across the industry is essential to align the entire supply chain with sustainability goals [102]. The historical trends indicate a pressing need for improved environmental performance, highlighted by the increase in hazardous waste generation despite technological advancements [29]. Collaborative efforts and regulatory mechanisms are crucial in facilitating ethical procurement practices, thereby enhancing sustainability within the semiconductor supply chain [100,102].

The semiconductor industry, particularly in the production of Wide-Bandgap (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN), faces significant challenges due to the depletion of critical resources such as silicon and gallium. To address these challenges, ongoing research is focused on enhancing material efficiency through innovations in nanotechnology, which allows for the development of devices that utilize fewer materials without compromising performance, thereby reducing environmental impact and aligning with sustainability goals [29]. Additionally, the adoption of green supply chain management practices is crucial for improving resilience and mitigating risks associated with resource scarcity [29]. The semiconductor foundry industry is also increasingly investing in renewable energy sources, such as solar power, to lower greenhouse gas emissions during manufacturing processes [14]. These combined efforts are essential for ensuring the long-term viability of WBG semiconductor production in the face of resource constraints and environmental concerns [103,104].

Government policies and regulatory frameworks are indeed pivotal in steering the semiconductor industry towards sustainable manufacturing practices. The European Union's Green Deal exemplifies this by setting ambitious emission reduction targets and promoting sustainable processes across industries, including semiconductors [105]. In the U.S., both federal and state initiatives incentivize investments in energy-efficient technologies, compelling companies to adopt greener practices [29]. This regulatory pressure not only ensures compliance with environmental standards but also fosters innovation, as companies seek to enhance sustainability while remaining competitive in a global market [14,92]. Furthermore, the semiconductor industry's inherent complexities necessitate a robust approach to green supply chain management, which can be facilitated by appropriate policies and regulations [29]. As the industry evolves, sustainability

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emerges as a critical driver of innovation, reinforcing the notion that environmental responsibility is integral to long-term competitiveness [24].

Table 2. Sustainability strategies in WBG semiconductor manufacturing, emphasizing their contributions to various environmental factors.

Sustainability Practice	Description	Impact on Recycling	Impact on Energy Consumption	Impact on Waste Reduction	Toxic By-product Elimination
Low-Energy Epitaxial Growth	Reduces energy required in the deposition of semiconductors	Low	High	Moderate	Moderate
Green Chemistry in Manufacturing	Utilizes environmentally friendly chemicals to replace harmful substances in production processes	Low	Moderate	High	High
Closed-Loop Recycling Systems	Recovers and reuses materials from semiconductor production waste (e.g., silicon wafers, gallium).	High	Low	High	Moderate
Reduction of Chemical Vapor Deposition (CVD)	Innovating CVD processes to minimize toxic emissions and lower energy demands	Low	High	Low	High
Recycling of Semiconductor Materials	Implements strategies for reclaiming materials like silicon carbide (SiC) and gallium nitride (GaN)	High	Low	High	Low
Advanced Wastewater Treatment	Integrates new filtration technologies to treat and reuse wastewater from production facilities	Low	Low	High	High
Energy Efficiency Measures	Incorporates energy-efficient equipment and renewable energy sources to power semiconductor production lines	Low	High	Moderate	Low

4. Applications of Wide-Bandgap (WBG) Semiconductors in Sustainable Technologies

Wide-bandgap (WBG) semiconductors, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN), have gained significant attention for their transformative impact on various industries, especially in the pursuit of sustainable technologies. These materials are driving innovation in electric vehicles (EVs), renewable energy systems, 5G infrastructure, smart grids, and other crucial

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applications (Figure 7). The integration of SiC and GaN in these technologies contributes to improved energy efficiency, reduced carbon emissions, and overall sustainability.

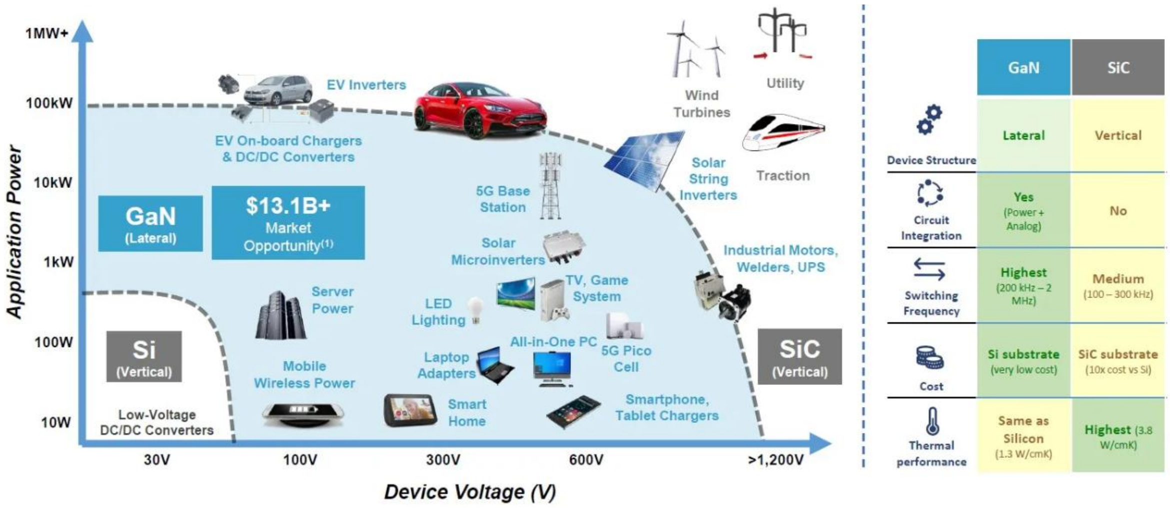

Figure 7. Si, SiC, and GaN opportunities (Source: Power Electronics News) [106].

Silicon Carbide (SiC) devices are transforming electric vehicle (EV) power systems (Figure 7) by significantly enhancing the efficiency of inverters and power modules. These components outperform traditional silicon systems, achieving efficiencies exceeding 95% and thereby minimizing energy losses during power conversion, which is crucial for optimizing energy use in EV traction inverters [53,107]. SiC technology allows for operation at higher voltages and temperatures, further reducing energy losses and improving powertrain efficiency, which translates into extended driving ranges and reduced recharging frequency [108]. Additionally, SiC's capability to handle higher switching frequencies facilitates faster energy transfer, leading to quicker charging times for EVs [109]. This efficiency not only enhances vehicle performance but also supports the transition to cleaner transportation by lowering energy consumption and reducing the carbon footprint of EVs, promoting sustainability in the automotive sector [108,110].

Gallium Nitride (GaN) transistors are revolutionizing renewable energy systems, particularly in solar inverters and wind turbine power electronics (Figure 7), due to their ability to handle high voltages and frequencies with minimal energy loss. This capability is crucial for managing the fluctuating nature of renewable energy sources, enhancing the robustness of designs in these applications [58,111]. GaN technology significantly improves power conversion efficiency, which facilitates better integration of renewable energy into power grids, leading to higher energy yields from solar panels and wind turbines [112,113]. By minimizing energy losses during power conversion, GaN devices not only support sustainability goals by maximizing output from renewable resources but also reduce overall energy waste [114]. As these systems become more efficient and reliable, the adoption of solar and wind energy is expected to increase, further decreasing reliance on fossil fuels and contributing to a cleaner, more sustainable energy future [113,114].

The integration of Gallium Nitride (GaN) semiconductors into 5G infrastructure (Figure 7) significantly enhances sustainability by enabling higher frequency operations with reduced power consumption compared to traditional silicon devices. This efficiency leads to lower energy usage in 5G base stations, which is crucial for meeting the growing data demands of modern communication networks while adhering to sustainable practices [58]. GaN's ability to minimize heat generation reduces cooling requirements, resulting in substantial energy savings [7]. The compact design of GaN-based equipment further decreases the energy and resources needed for infrastructure development, facilitating faster data transmission with lower energy consumption [115]. GaN and Silicon Carbide (SiC) devices improve smart grid efficiency by reducing energy losses during transmission and distribution, optimizing grid performance, and supporting the integration of

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renewable energy sources [116]. This combination of advancements promotes sustainability through the effective utilization of clean energy resources and enhances overall grid stability [117].

Sectors other than electric vehicles and renewable energy systems (Figure 7) have been the nascent target of Wide-Bandgap semiconductors. In aerospace and military applications, these materials are essential for high-temperature and high-power systems, enhancing reliability and energy efficiency in mission-critical operations under extreme conditions [41,58]. Their superior properties, such as high breakdown voltage and good thermal conductivity, greatly improve their performance while cutting down on energy consumption [41]. In consumer electronics, WBG semiconductors are increasingly used in chargers and power supplies, leading to lower energy consumption in everyday devices [2]. This transition not only aligns with sustainability goals by promoting efficient technologies but also helps minimize electronic waste [118]. As WBG technologies continue to evolve, they are poised to drive innovation and support the global shift towards greener technologies across multiple industries [2,7].

5. Challenges and Future Prospects of Wide-Bandgap (WBG) Semiconductors

To fully realize the potential and enable the widespread adoption of WBG semiconductors, several significant challenges must be addressed. These challenges span across cost and scalability, material availability, integration with existing technologies, and environmental sustainability, each of which will be explored in detail.

Cost and Scalability

The high cost and complexity of producing Wide-Bandgap (WBG) semiconductors, such as SiC and GaN, significantly hinder their large-scale adoption. Despite advancements in fabrication techniques, these processes remain intricate and expensive, leading to lower production yields compared to traditional silicon semiconductors, which complicates achieving necessary economies of scale [119]. The capital-intensive nature of WBG semiconductor production, particularly the requirement for specialized equipment and cleanroom environments, poses additional challenges for scaling up manufacturing [119]. The production of vertical-cavity surface-emitting lasers (VCSELs) from materials like Gallium Arsenide (GaAs) and Aluminum Gallium Arsenide (AlGaAs) faces issues related to thickness and wavelength uniformity, which exemplify the broader difficulties in manufacturing next-generation semiconductors [119]. These limitations collectively inhibit mass production, which is essential for the widespread implementation of WBG technologies [119,120].

Future Prospects; The future of manufacturing techniques for Wide-Bandgap (WBG) semiconductors, particularly Gallium Nitride (GaN), is focused on enhancing scalability and reducing production costs through automation and advanced wafer technologies. Research indicates that improvements in manufacturing processes, such as Metal-Organic Vapor Phase Epitaxy (MOVPE), are essential for achieving uniformity and yield in larger diameter wafers, which is critical for applications in photonics and beyond [119]. The semiconductor industry is increasingly prioritizing energy-efficient chips and sustainable practices, driven by environmental concerns and market demands [121]. The life cycle impacts of WBG materials, including their energy consumption and greenhouse gas emissions, are also being evaluated to support a circular economy [49]. As these innovations unfold, they will be pivotal in realizing the potential of WBG semiconductors in sustainable applications like electric vehicles and renewable energy systems, ultimately contributing to an eco-friendlier technological landscape [59,122].

Material Availability and Sustainability

The transition to Wide-Bandgap (WBG) semiconductors faces significant challenges related to material availability and sustainability. The limited supply of these critical materials, exacerbated by global competition, creates vulnerabilities in the supply chain that can delay production and hinder the adoption of WBG technologies [123]. The extraction and refinement processes for SiC and GaN are energy-intensive, contributing to their environmental footprint, which is a growing concern in

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the context of sustainable development [124,125]. The demand of these materials by the automotive and construction industries is increasingly high because of their ever-growing need for lightweight yet highly efficient materials. This may lead to further price volatility, thus complicating the sustainable transition towards electric vehicles and other advanced technologies [126,127]. Addressing these challenges requires coordinated efforts in research and development, as well as the exploration of alternative materials that minimize environmental impacts [124].

Future Prospects: Research into alternative materials and advanced recycling processes is crucial for addressing the risks of raw material shortages, particularly in the context of the semiconductor industry. The European Union has recognized the importance of critical raw materials (CRMs) and is actively promoting innovative recycling technologies to enhance material recovery from electronic waste, such as Printed Circuit Boards (PCBs) and Rare Earth Permanent Magnets (RE-PMs) [128]. The construction industry's shift towards using waste materials exemplifies the broader movement towards a circular economy, which emphasizes resource conservation and waste reduction [129]. Integrating sustainable materials into supply chains can significantly reduce carbon footprints and enhance resilience, although challenges such as higher costs and regulatory complexities remain [130]. The need for comprehensive policies and harmonization across EU member states is essential to facilitate the transition towards sustainable practices and ensure a stable supply of essential materials for industries like semiconductors [131,132].

Integration with Existing Technologies

The transition from traditional silicon-based semiconductors to Wide-Bandgap (WBG) semiconductors poses significant integration challenges for existing technologies. Industries like automotive and telecommunications must invest heavily in upgrading their infrastructures to accommodate these new materials, which can delay widespread adoption due to the substantial modifications required for power electronics and thermal management systems [2,49]. The integration process is complicated by issues such as lattice mismatches, which can lead to defects that adversely affect the performance and reliability of WBG devices [133]. To address these challenges, advanced device architectures must be developed to optimize performance while ensuring manufacturability, thereby facilitating a smoother transition to WBG technologies [134,135]. Ultimately, overcoming these integration hurdles is crucial for unlocking the full potential of WBG semiconductors in modern applications.

Future Prospects: The transition from silicon to Wide-Bandgap (WBG) semiconductors is being facilitated through hybrid technologies that allow for the coexistence of both materials, enabling industries to adapt gradually without extensive system overhauls. For instance, the Si/WBG hybrid half-bridge converters optimize power-sharing and switching frequency, achieving significant reductions in power loss while maintaining performance quality, thus demonstrating a practical approach to integrating WBG devices with existing silicon technology [136]. The use of WBG materials like SiC and GaN in power converters enhances efficiency and performance in electric vehicles, addressing the growing demand for high power density and efficiency [2,11]. Ongoing research into defect control and device optimization, particularly in Ultrawide-Bandgap materials, is crucial for improving their reliability and performance, which will further accelerate their adoption across various sectors [13]. This gradual integration model is essential for meeting industry demands while minimizing disruption [137].

Ultrawide-Bandgap (UWBG) Materials

Ultrawide-Bandgap (UWBG) materials, including Diamond, Gallium Oxide (Ga_2O_3), and Aluminum Nitride (AlN), are poised to revolutionize high-power applications due to their superior performance characteristics compared to traditional Wide-Bandgap (WBG) semiconductors. These materials can enhance energy efficiency, minimize energy losses, and facilitate the miniaturization of high-power devices, which is essential for sectors like aerospace and high-voltage power grids [5,13]. Significant challenges persist in their fabrication, such as high production costs, defects during synthesis, and the difficulty of producing large, defect-free wafers [82,138]. These manufacturing limitations are reminiscent of those encountered with WBG semiconductors, underscoring the urgent need for innovative production techniques to enable the widespread adoption of UWBG materials in advanced electronic applications [13,42].

Future Prospects: Ongoing research into Ultrawide-Bandgap (UWBG) materials is crucial for overcoming existing barriers related to their fabrication and performance. The challenges include achieving bipolar electrical conductivity and effective doping, particularly for p-type regions, which are essential for high-voltage applications [138,139]. Investments from both public and private sectors are vital to develop cost-effective and scalable production technologies, which can enhance the understanding and application of UWBG materials like AlGaN, Ga_2O_3, and Diamond [5,13]. Improved fabrication methods, such as magnetron sputtering for p-type doping, are being explored to create high-performance devices that can operate efficiently under extreme conditions [139]. Addressing these challenges could lead to significant advancements in high-power applications, paving the way for the next generation of energy-efficient technologies that leverage the superior properties of UWBG semiconductors [5,13].

Long-Term Sustainability and Environmental Impact

Wide-Bandgap (WBG) semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), offer significant advantages in reducing energy consumption and carbon emissions in power electronics applications due to their superior performance characteristics [7,140]. However, the production processes for these materials are energy-intensive and raise sustainability concerns. The semiconductor foundry industry has seen a substantial increase in hazardous waste generation, with a 239% rise in absolute values over the past decade, despite advancements in renewable energy usage that have reduced greenhouse gas emissions per manufacturing index by 32% [14]. The challenges associated with material extraction and processing of WBG semiconductors necessitate a shift towards more environmentally conscious practices to mitigate their ecological footprint [5]. Addressing these issues is crucial for ensuring that the benefits of WBG technologies do not come at the expense of long-term environmental sustainability [141].

Future Prospects: To align with global sustainability goals, the semiconductor industry must prioritize energy-efficient fabrication techniques and the use of renewable energy sources in production facilities. Recent studies highlight that the industry's energy-intensive processes contribute significantly to environmental degradation, with a notable increase in hazardous waste generation over the past decade [14]. The development of greener chemical processes, such as the use of environmentally friendly corrosion inhibitors in Chemical Mechanical Planarization (CMP) slurries, is crucial for reducing the environmental footprint of semiconductor manufacturing. Adopting a green supply chain management approach can enhance sustainability by addressing technological risks and improving resource utilization [29,142]. As the semiconductor industry evolves, it is essential to invest in research and development to create energy-efficient technologies and minimize electronic waste, ensuring that advancements in Wide-Bandgap (WBG) semiconductors contribute to a cleaner and greener future [121,142].

6. Conclusions

Wide-bandgap (WBG) semiconductors, particularly silicon carbide (SiC) and gallium nitride (GaN), represent a key advancement in the quest for higher energy efficiency and performance in high-power applications. However, their production methods remain energy-intensive, with significant environmental challenges such as high carbon emissions and waste generation. To mitigate these impacts, the integration of green manufacturing practices, including energy-efficient epitaxial growth, the adoption of circular economy principles, and the development of low-toxicity chemicals for wafer processing, is critical. Additionally, innovative recycling techniques for recovering materials from end-of-life WBG devices can substantially reduce electronic waste.

Future research should prioritize improving the sustainability of ultrawide-bandgap (UWBG) materials like gallium oxide (Ga_2O_3) and diamond, which offer even greater performance but face similar environmental hurdles. These innovations, combined with more stringent regulatory frameworks and industry collaboration, can pave the way for WBG semiconductors to contribute meaningfully to global sustainability goals in sectors such as renewable energy, electric vehicles, and telecommunications. Addressing these challenges head-on will be essential for balancing the growth of WBG technologies with the environmental responsibilities of the semiconductor industry.

Author Contributions: The manuscript was written through contributions of all authors. All authors have approved the final version of the manuscript.

Data Availability Statement: No data was used for the research described in the article

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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