

Advanced Electronics: The Emergence, Evolution, and Future of Gallium Nitride Technology

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Abstract. Gallium nitride (GaN) is a desirable substance for electronics that require high frequencies and high power. The research and development of vertical GaN devices on GaN substrates has made significant progress in recent years, thanks to the availability of high-quality free-standing bulk GaN substrates. Despite some inherent difficulties associated with substrate fabrication and the intricate process of metal doping for sensor applications, the prospects for the future of GaN appear quite encouraging. As a result, various transistors and diodes with excellent characteristics have been reported. This essay explores the trajectory of Gallium Nitride (GaN) and its transformative influence on the field of electronic technology. It starts from the distinctive characteristics of GaN, including its broad bandgap, Wurtzite structure, and remarkable thermal conductivity, within the framework of its historical progression, spanning from its initial synthesis to its significant contribution to energy-efficient lighting and 5G technologies. The progress made in the manufacturing processes of GaN, which have shifted towards more sustainable and efficient methods, is also discussed. It also explores the innovative applications of GaN in high-frequency power electronics and optoelectronics, emphasizing its importance in enhancing device efficiency and facilitating environmental monitoring.

Keywords: Gallium Nitride, Wurtzite structure, High-frequency electronics, Optoelectronics, Energy efficiency.

1. Introduction

In the rapid development of electronic technology, the evolution of materials has played a vital role in deciding the capabilities and applications of devices that characterise our present era. Gallium Nitride (GaN) is a notable example of the progress achieved in material science. GaN has exceptional qualities and adaptability, offering a glimpse into the forthcoming advancements in electronics [1].

This essay will analyse the developmental chronology, inherent characteristics, manufacturing methodologies, and innovative applications of GaN, emphasising the significance of GaN not only as a substance but also as a prognosticator of forthcoming electronic and optoelectronic devices. It holds great importance in the field of electrical technology, as it encompasses not only its material features but also represents the collective endeavours and intellectual inquisitiveness of the worldwide scientific community. The narrative commences by documenting the several stages of GaN's development, starting from its initial synthesis, and culminating in its Nobel-acknowledged contribution to energy-efficient lighting. This highlights the parallel progress of the material with advancements in technology. After providing a historical review, the essay explores the fundamental features that distinguish GaN, such as its wide bandgap and the Wurtzite crystal structure. These qualities establish the foundation for GaN's extraordinary performance in challenging conditions. The investigation proceeds by conducting a thorough analysis of the advancements in GaN production and processing technologies, emphasising the transition towards more environmentally friendly and productive methods. Furthermore, the essay explores the revolutionary uses of GaN in high-frequency power electronics and optoelectronics, demonstrating its significant influence on improving device efficiency and creating new opportunities in communication, sensing, and environmental monitoring.

2. Basic theory analysis

2.1. The Development history and trend of GaN

Tracing the ancestry of GaN reveals a story of scientific pursuit and discovery that spans many years, highlighting important achievements that have greatly influenced the field of semiconductor technology. GaN, a compound semiconductor, was first synthesised in the early 1930s using the process of pouring ammonia over liquid gallium at high temperatures. However, its practical application did not occur until dozens of years later [2]. In the early 1970s, the original concept of the light-emitting diode (LED) was introduced, but it needed a high voltage to produce violet light. The initial testing established the foundation for GaN's eventual supremacy in optoelectronic devices that can emit with great efficiency in the blue and green spectrums. This is crucial for optical wireless communication and other applications. The material's progression was characterised by a combination of difficulties and advancements, including overcoming the fragility of gallium arsenide and mastering the deposition methods necessary for producing GaN films of superior quality. GaN-based materials emerged as a crucial component for Industry 4.0 at the turn of the millennium, offering advantages such as reduced gate capacitance, decreased drive loss, and increased switching frequencies in comparison to earlier materials. The conclusion of GaN's journey of development was widely acknowledged when the 2014 Nobel Prize in Physics was given for the creation of efficient blue LEDs, demonstrating GaN's significant influence on lighting technology. This bibliometric analysis comprehensively examines the extensive development history of GaN and highlights its diverse range of applications, including 5G technologies and power electronics. It emphasises the material's ability to withstand radiation and its exceptional thermal conductivity [2, 3]. The journey of GaN, from being a mere subject of curiosity in laboratories to becoming a fundamental component of advanced electronic and optoelectronic systems, is a story of persistent pursuit of knowledge. This progress has been achieved through coordinated multinational endeavours that constantly challenge the limits of technological possibilities.

2.2. The Basic Characteristics of GaN

As a binary III/V direct bandgap semiconductor, GaN is commonly used in high-frequency and power electronics because its outstanding electronic properties and physical performance make itself suitable for use in harsh environments. With a wide bandgap of 3.4 eV, it operates stably at high temperatures and voltages with minimal leakage currents and sound electron mobility [4]. The Wurtzite structure is shown in figure 1.

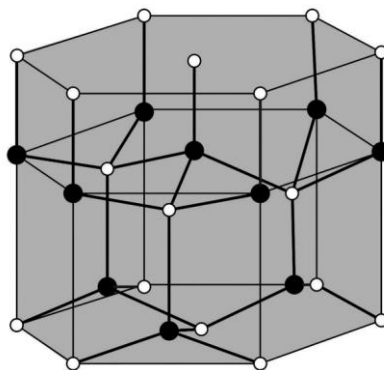


Figure 1. Wurtzite Structure [4]

The GaN material has a complex crystal structure known as the Wurtzite structure, which serves as a captivating demonstration of its hexagonal symmetry at the atomic scale. The unusual electrical and optical capabilities of GaN are attributed to its distinctive hexagonal close-packed framework, which is a defining characteristic of this structure. The relevance of the Wurtzite configuration of GaN, characterized by a precise arrangement of atoms in a hexagonal lattice, lies in its ability to provide high efficiency in optoelectronic devices and semiconductors. At the core of this arrangement lies the

arrangement of atoms in a manner that maximizes the electrical conductivity and light emission capabilities of GaN, hence establishing the foundation for its utilization in a diverse range of advanced technologies. The structural configuration of GaN is not solely a fixed attribute, but rather a dynamic factor that influences its interaction with electrical currents and light. This aspect contributes to the progress made in LED technology, high-frequency transistors, and laser devices [5, 6]. This analysis not only reveals the current capabilities of the material but also outlines a path for future advancements, thereby solidifying GaN's prominent position in the field of material science and engineering.

2.3. The Manufacturing and Processing Technologies for GaN

The manufacturing and processing technologies for GaN electronic devices have undergone a remarkable evolution, reflecting a concerted effort within the semiconductor industry to leverage GaN's superior electronic properties for high-power and high-frequency applications. As delineated by Liu et al., the journey from traditional gold-based metallization processes for III-V semiconductor devices to contemporary CMOS-compatible, gold-free techniques underscores a significant technological paradigm shift [7]. This transition not only aligns with the industry's push towards more cost-effective and scalable manufacturing practices but also caters to the stringent requirements of modern electronic systems for enhanced performance and reliability. The advent of novel technologies, such as regrown ohmic contacts and Metal-Insulator-Semiconductor (MIS) gate structures, epitomizes the innovative strides made in refining GaN device fabrication. These advancements not only improve device efficiency and longevity but also pave the way for the integration of GaN devices into a broader array of electronic applications.

Moreover, the exploration into vertical GaN device technologies heralds a new chapter for high-power applications, offering a promising avenue for achieving higher current densities and thermal management efficiencies. This progress is pivotal in realizing GaN's potential in sectors demanding robust power solutions, from renewable energy systems to electric vehicle powertrains. Concurrently, the bibliometric analysis provided by Lam, Lam, & Lee captures the expansive research and development trajectory of GaN, highlighting the material's evolutionary path from a laboratory curiosity to a cornerstone of next-generation electronic and optoelectronic systems [2]. The synthesis of this body of work not only charts the technological ascendancy of GaN but also encapsulates the collaborative spirit of the global research community in pushing the boundaries of semiconductor technology.

3. The Innovative Application of GaN in High-Frequency, Power Electronics, and Optoelectronics

The direct bandgap characteristic of GaN not only optimises its efficiency in the realm of optoelectronic apparatuses, such as LEDs and laser technologies, but also fosters an expansive integration into various optoelectronic domains [8, 9]. This feature is a pivotal factor in its ubiquitous presence across the optoelectronics landscape. Further augmenting the versatility of GaN, the advent of GaN-based Junctionless Accumulation Mode Nanowire Field-Effect Transistors (GaN-JAM-NWFET) marks a significant milestone, showcasing unparalleled efficacy in the manipulation of terahertz frequencies. Such advancements underscore the material's transformative potential in enhancing the precision and efficiency of radiofrequency communication frameworks and radar methodologies [10]. The strategic incorporation of transition metals like Copper (Cu), Silver (Ag), and Gold (Au) into the GaN matrix emerges as a sophisticated approach to modulating its electronic attributes. This deliberate modification not only amplifies the material's sensitivity but also tailors its responsiveness, making it an indispensable component in the fabrication of environmental sensors aimed at the meticulous detection of insidious pollutants such as Hexabromodiphenyl Ether. The synergy of GaN's extensive bandgap, superior electron mobility, and intrinsic stability, when intertwined with the momentum of ongoing technological evolution, is steadily carving new vistas for its application across a spectrum of modern electronic and optoelectronic endeavours, hinting at

a future where GaN's contributions are both foundational and transformative in the advancement of electronic and optoelectronic innovation [9].

The transformative impact of GaN in the field of advanced materials science is vividly illustrated through its myriad applications, ranging from high-frequency electronics to optoelectronic devices, each domain benefiting from GaN's exceptional electronic and physical properties. A quintessential example is found in the development of high-power GaN-JAM-NWFETs, which have been demonstrated to exhibit remarkable performance in terahertz applications, underscoring the material's potential to revolutionize radiofrequency communication and radar systems [10]. This advancement not only speaks to GaN's efficiency in handling high frequencies but also its capability to operate under the demanding conditions of high power and temperature, characteristics that are intrinsic to its robust crystal structure and superior electron mobility.

Further extending GaN's realm of influence, the doping of GaN with transition metals such as Cu, Ag, and Au has been explored to enhance its sensitivity and responsiveness in environmental sensors. These sensors are adept at detecting emerging pollutants like Hexabromodiphenyl Ether, showcasing GaN's versatility and its contribution to environmental monitoring [11]. The strategic manipulation of GaN's electronic properties through doping reveals the material's adaptability and the breadth of its application spectrum.

Moreover, the bibliometric analysis provided by Lam, Lam, & Lee delineates the expansive research trajectory of GaN, from its historical development in optoelectronics to its pivotal role in the advent of 5G technology, highlighting the global research community's vested interest in leveraging GaN's unique properties for cutting-edge applications [2]. This collective scholarly effort has not only advanced our understanding of GaN but also laid down a fertile ground for future technological breakthroughs.

In the context of crystalline structures, the Wurtzite structure of GaN plays a crucial role in its functionality. The alignment and periodic arrangement of atoms within this structure contribute significantly to GaN's high efficiency in electronic and optoelectronic devices, as elucidated in the foundational work on crystal structures by Galsin [5]. The interplay between GaN's atomic structure and its material properties exemplifies the critical importance of crystallography in the material's application and performance.

4. The Challenges and Prospects of GaN

Gallium Nitride (GaN) is making significant advancements in the field of semiconductor technology, offering the potential for groundbreaking changes. However, it is also facing a complex set of intricate difficulties. GaN's durability in high-voltage settings and its flexibility in high-frequency tasks have the potential to revolutionise power electronics and optoelectronics. However, there are numerous challenges that hinder its progress [4]. The production of GaN, specifically high-quality substrates without defects, continues to be a difficult task. This is crucial for unlocking the full potential of GaN in devices such as the GaN-JAM-NWFET, which has demonstrated remarkable capabilities in manipulating terahertz frequencies. However, the device still faces limitations due to imperfections in the material [10]. In addition, the groundbreaking approach of introducing transition metals like Cu, Ag, and Au into GaN to enhance its sensitivity for environmental sensors that detect complex pollutants like Hexabromodiphenyl Ether represents a double-edged sword. On one hand, it advances the functionality of the sensors, but on the other hand, it requires careful management of the material's integrity [11].

However, there are promising opportunities for Gallium Nitride (GaN) in the future. The unwavering endeavour to overcome these obstacles in material and manufacturing stimulates the effort to not only enhance the inherent capabilities of GaN but also broaden its range of applications. The current efforts to reduce substrate flaws and fully understand the complexities of metal doping are facilitating the incorporation of GaN into future devices. The landscape of GaN technology is advancing due to

extensive research and innovative engineering. This progress is leading to a wide range of applications, including the transformation of power electronics and optoelectronics, as well as the development of new approaches to environmental monitoring and other areas. The evolution of GaN, characterised by its challenges and successes, serves as evidence of humanity's unwavering quest for technological expertise and innovation, offering a future in which today's obstacles transform into tomorrow's accomplishments [2, 3].

5. Conclusion

This essay has assessed the revolutionary path of Gallium Nitride in electronic technology. It has highlighted important milestones in its historical development and prospects. The distinctive characteristics of GaN, such as its Wurtzite structure, enables high efficiency in optoelectronic devices and semiconductors. Furthermore, the advancements in the manufacturing technology of GaN not only improve the efficiency and longevity of GaN but also pave the way for the integrated GaN devices into a broader array of electronic applications, including the innovative applications of GaN in high-frequency power electronics and optoelectronics that illustrate the critical role of GaN in enhancing device performance and enabling technologies that were once considered to be unattainable. In addition, GaN's ability to operate under extreme conditions and its superior electron mobility have positioned it as a key material in the development of environmentally sensitive sensors and energy-efficient lighting solutions, marking a significant step towards sustainable technological advancements. The collective efforts in researching and developing GaN-based technologies reflect a global commitment to overcoming the challenges associated with semiconductor materials, thereby unlocking new possibilities for their application across various industries. Hence, GaN has promising opportunities in the future despite some existing challenges.

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