

Exploring The Potential of Graphene and Gallium Nitride: Novel Semiconductor Materials in The Modern Era

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Abstract. This article presents an in-depth exploration of two cutting-edge semiconductor materials: graphene and gallium nitride. It examines their structural characteristics, applications, and future potential in the context of advancing science and technology. Graphene, a remarkable material, exhibits exceptional theoretical properties, making it a versatile contender for a wide range of applications. Gallium nitride, on the other hand, finds its strength in power and wireless base stations, offering distinct advantages in specific domains. One common challenge faced by both materials is their high production cost, complexity, and limited output. However, it is foreseeable that ongoing research will overcome these hurdles, propelling graphene, and gallium nitride into the forefront of technological innovation. As science and technology continue to progress, these two materials are poised to play increasingly significant roles across various industries. Their remarkable attributes and evolving feasibility will likely draw greater attention from researchers and industry stakeholders alike, shaping the technological landscape of the future. This article's comprehensive analysis provides valuable insights into the potential of graphene and gallium nitride, offering a foundation for further research and development in the field of semiconductor materials.

Keywords: Semiconductor Materials, Graphene, Gallium Nitride, Advanced Technology.

1. Introduction

In recent times, a remarkable revelation has emerged within the realm of semiconductor devices, traditionally reliant on materials like silicon. This revelation stems from the relentless march of progress in science and technology, which has rendered these conventional materials inadequate in delivering the high-performance standards demanded by contemporary applications [1]. Consequently, there has been a concerted effort to seek alternatives to silicon, leading to the creation of a plethora of novel semiconductor materials. Among the standout contenders in this pursuit are graphene and gallium nitride, both of which have garnered substantial attention and acclaim owing to their exceptional properties [2]. Concurrently, scientists have embarked on a comprehensive exploration of their unique characteristics and the feasibility of large-scale production.

This article primarily delves into the fascinating world of gallium nitride and graphene, offering an insightful juxtaposition of these two remarkable materials. First and foremost, it elucidates the intricate structures and distinctive traits inherent in each. Subsequently, it engages in a thorough examination of the merits and demerits associated with these materials, highlighting their respective strengths and weaknesses. Moreover, the article delves into their diverse array of applications and provides a glimpse into the promising prospects for future advancements in these domains.

The significance of this article lies in its multifaceted analysis of graphene and gallium nitride. This comprehensive exploration holds the potential to greatly benefit ongoing research endeavors, shedding light on the intricate intricacies of these materials and paving the way for groundbreaking innovations in the semiconductor industry.

2. Theoretical basis analysis

2.1. Structural properties

2.1.1 Gallium Nitride(GaN)

Gallium and nitrogen combine to form gallium nitride (GaN). It has a Wurtzite crystal structure and is a Group III and Group V direct bandgap semiconductor. Figure 1 is gallium nitride's structure [3].

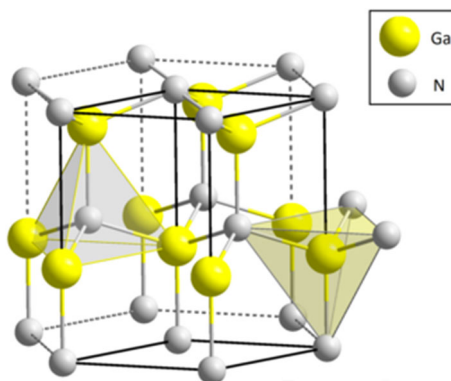


Fig. 1 Gallium nitride's structure [3]

Wide-bandgap semiconductor material GaN is mechanically stable and has strong thermal conductivity and heat capacity. The Knoop hardness of the object is 14.21 GPa-4, which is high. It can be used as a thin coating on sapphire or silicon carbide despite having a different lattice constant, and it is less likely to crack. GaN can produce n- or p-type materials when doped with silicon (Si), oxygen (O₂), or magnesium (Mg) [4]. However, Si and Mg atoms can affect the formation of GaN crystals, causing them to become brittle and more prone to tensile stress. Gallium nitride compounds frequently have dislocation densities between 10⁸ and 10¹⁰ faults per square centimeter, which are also high. The U.S. Army Research Laboratory (ARL) performed the first measurements of the high-field electron velocities in GaN in 1999. ARL researchers experimentally attained a maximum steady-state velocity of 1.9×10^7 cm/s with a transit duration of 2.5 picoseconds in an electric field of 225 kV/cm. Electron mobility is computed using this data, and the results are used to guide the design of GaN devices.

2.1.2 Graphene

A carbon allotrope called graphene is made up of single sheets of atoms arranged in a hexagonal nanostructure. In Figure 2, its structure is displayed [5].

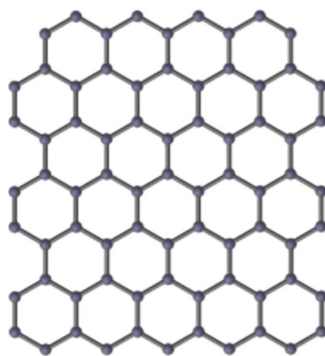


Fig. 2 Graphene structure [5]

A valence band that spans the entire graphene sheet is created by the σ and delocalized π bonds that link each atom in the structure to its three nearby atoms. This type of bonding is also present in glassy carbon, fullerenes, PAHs, and (to a lesser extent) carbon nanotubes. The hypothesis of massless relativistic particles [6] provides the best explanation for how the conduction band

interacts with the valence band to turn graphene into a semimetal with unique electrical characteristics. Bipolar field-effect transistors can be made from graphene because the energy of charge carriers in this material depends on momentum in a linear rather than a quadratic way. The material displays enormous nonlinear diamagnetism and massive quantum oscillations, and charge transport over large distances is ballistic. Along the graphene planes, heat and electricity are conducted exceedingly well. Although graphite seems black because the material absorbs nearly all visible light wavelengths, individual graphene sheets are actually transparent due to their extreme thinness. When compared to the toughest steel of the same thickness, the substance is roughly 100 times stronger.

2.2. The benefits and difficulties of these semiconductors

The benefits of GaN and graphene are many. GaN has a larger bandgap than traditional silicon materials, giving it a very narrow depletion region, allowing the development of device structures with very high carrier concentrations, which directly determine the conductivity of the semiconductor. It also has the characteristics of high efficiency, low loss, and high frequency. For graphene, it is extremely durable and flexible for graphene, one of the strongest known materials, and has excellent optical, thermal, and electrical conductivity properties [7].

Although gallium nitride and graphene are two excellent semiconductors, they still have some drawbacks. For gallium nitride, it has several shortcomings that cannot be ignored. For instance, gallium nitride materials are very expensive to produce, the technology is complex, and the production capacity is extremely low, GaN cannot be produced as a single crystal using the CZ method, unlike conventional materials. The standard production procedure at the moment involves creating a 1 mm thick GaN coating on other crystal surfaces, which is then peeled off, polished, and used as a GaN substrate. The production is already quite low and can only be manufactured up to a thickness of 1 mm at a time [8]. Due to factors including polycrystals encircling the single crystal and internal crystal flaws, peeling off different crystals frequently results in tension building that causes substrate rupture. Also, the yield of producing gallium nitride is very low, so this material is still not widely popularized.

The situation with graphene is even more difficult. First, large-scale graphene production is challenging and expensive. Typically, mechanical exfoliation is used to create modest quantities of graphene sheets. However, huge quantities of graphene sheets must be removed for commercial production, which is exceedingly challenging because the retrieved material will also have some impurities and flaws. It costs a lot of money to make graphene sheets without flaws. At the moment, graphene costs roughly \$100 for one gram. Although graphene is 100 times stronger than steel, commercialization will take years to create adequate production techniques if a single sheet costs \$100 to produce. Second, graphene reacts violently with heat and oxygen. Graphene itself is not very stable, although it has good thermal conductivity qualities. One significant drawback of graphene is its inability to endure steadily in an aerobic atmosphere. It can produce graphene oxide, which loses graphene's inherent characteristics and its capacity to conduct electricity, if it reacts with oxygen at high temperatures [9]. Third, the most significant issue with graphene is that it cannot be turned off, despite being a good conductor. It cannot be switched off since it has no semiconducting characteristics due to the zero bandgap. Fourth, some toxins and contaminants can be produced during the processing of graphene sheets. When graphite is heated to make graphene, hazardous compounds and impurities are released. This could negatively affect graphene's performance as well as endanger people. And the last one is when produced, graphene that is less than 20 nm in size becomes unstable. The top layer of graphene oxide cracks when graphene undergoes cross-plane oxidation, resulting in irregular dimensions and the inability to generate large-sized sheets.

From table 1, this can find that graphene is better than gallium nitride in some properties, but graphene is too expensive and hard to produce, and it does not have a bandgap for now. Despite the fact that making graphene is incredibly challenging, it will be a direction of development and it will be an important material in the future.

Table 1. The comparison between Gallium Graphene

Characteristic	Relative molecular mass(10g/mol)	Melting point(1000 K)	Bandgap(1eV)	Electron mobility(m ² /Vs)	Thermal conductivity(W/cmK)	Refractive index
GaN	8.37	1.33	3.4	1.5	1.3	2.43
Graphene	1.2	4.51	0	15	5.3	1.7

3. Application analysis

3.1. Gallium nitride applications and future development

3.1.1 Applications of gallium nitride in various fields

Gallium nitride is widely used in different fields due to its superior material properties. Here are some examples of applications of gallium nitride.

LEDs and lasers. Gallium nitride, which has a big bandgap, high breakdown voltage, large thermal conductivity, high electron saturation drift speed, strong radiation resistance, and good chemistry, is mostly employed as a semiconductor material in the LED sector. Stability and other outstanding qualities.

Power component. Gallium nitride is frequently used in electrical components, such as chargers. This is due to gallium nitride devices having substantially lower on-resistance values per unit area at the same rated voltage. GaN chips and their packaging can be made considerably smaller as a result. GaN devices flip so quickly from a system perspective that they can also achieve higher switching frequencies, lower the size of passive components, and, in some cases, eliminate the need for mechanical heat dissipation [10]. GaN FETs and integrated circuits can be used to reduce the total weight and size of the final solution. Additionally, it might offer higher efficiency and more power density, gallium Nitride devices provide record power densities and efficiency in a range of applications because they greatly enhance switching performance and shrink in size. One such is the 48 V power supply needed for high-density computing tasks in cloud computing, AI, machine learning, and gaming applications. Smaller form factors are made possible by high efficiency and high-power density converters, which also lower system-level power consumption. In a 48 V/12 V power converter that delivers 1 kW of power to a 12 V load with a peak efficiency of 96.3%, a GaN device-based reference design achieves previously unheard-of power density (>4 kW/in³) for this application. When, the module measures 17.522.87.7 mm and has a 93.8% efficiency. The thermal performance of GaN is also good too, energy is lost as heat during operation of a gallium nitride device. As a result, it is crucial to consider how well the gadget transfers heat to the environment. The GaN FET has a substantially smaller size than MOSFET devices with a same on-resistance, yet it has superior absolute thermal performance [11]. In fact, the junction-to-case path has good thermal conductivity since the thermal resistance (RJC) of chip-scale GaN transistors to cases is lower than that of silicon devices.

Communication base station. When compared to high-frequency technologies like gallium arsenide and indium phosphide, gallium nitride devices have better power output, and they have better frequency characteristics when compared to power processes like silicon carbide and LDCMOS. The usage of carrier aggregation technology, the planning of adopting higher frequency carriers, and the importance of gallium nitride devices increased instantaneous bandwidth are all efforts to increase bandwidth. Gallium nitride is quicker and capable of higher power density than silicon or other technologies. GaN's advantage of being tiny is that it can operate at a given power level. Device capacitance can be decreased with smaller devices, simplifying the design of systems with larger bandwidth. The power amplifier is a crucial part of RF circuits. From the perspective of contemporary applications, gallium arsenide power amplifiers and complementary metal oxide semiconductor power amplifiers—of which GaAs PA is the predominant type—make up the majority of power

amplifiers. Gallium arsenide devices, however, won't be able to match the demands of the market once 5G is available. Keeping up with such a high frequency while maintaining a high level of integration [12]. GaN has consequently emerged as the newest hot spot. Wide-bandgap semiconductor gallium nitride can withstand greater operating voltages, raising its power density and operating temperature. As a result, it possesses qualities like high power density, low energy consumption, suitability for high frequency, and support for wide bandwidth.

3.1.2 Future development

In the fields of optoelectronics, high-temperature, high-power, and high-frequency microwave devices, gallium nitride has a wide range of potential applications. GaN will take up greater space in telecoms macro base stations, vacuum tubes in radar, and avionics applications as 5G high-frequency communications become commercially viable.

3.2. Graphene applications and future development

3.2.1 Applications of graphene in various fields

Applications in the battery. Batteries made of graphene can have a smaller negative effect on the environment. The structure of a graphene battery is similar to that of a conventional battery, with two electrodes and an electrolyte solution to aid in ion transfer. The composition of one or two electrodes is the primary distinction between graphene batteries and solid-state batteries. Although allotropes of carbon can also be used at the anode, changes largely take place at the cathode. In contrast to conventional batteries, which have a pure solid cathode, graphene batteries have a composite cathode, or a hybrid material made of solid metal and graphene [13]. Depending on the intended use, the composite's graphene content can change. In most cases, the amount of graphene added to an electrode is determined by the desired performance and is based on the efficiency or flaws of the solid precursor material.

Graphene coating. A variety of graphene coating products have been used internationally, and the technology for coating with graphene is still in its infancy. It is impossible to separate the exceptional performance of graphene in optics, electrical, thermodynamics, and tribology from the fact that it can be made into coatings. For instance, the unique two-dimensional lamellar structure of graphene is chemically stable. The coating's stacking fault pattern not only creates a physical barrier that prevents corrosive media from penetrating it, but also has a huge surface area, requiring less graphene. It can serve as a physical barrier and shield. Additionally, due to graphene's distinct two-dimensional layered structure and dispersion in the heat-dissipating coating, heating-related organic coating deformation and flow can be postponed [14]. Furthermore, heat is swiftly distributed across the layer thanks to graphene's excellent thermal conductivity within the layer. In addition, because graphene has relatively low thermal conductivity between its layers, it possesses excellent internal and external thermal insulation properties. It creates a significant temperature difference between the coating's inner and exterior surfaces, assisting in the protection of temperature-sensitive machinery. Additionally, magnetic particles doped with graphene can ensure that a material has significant magnetism as well as conductivity, and they can be used in conjunction with other functional coatings to achieve specific goals like electromagnetic shielding.

3.2.2 Future developments

Graphene research and application development are both gaining steam. In battery electrode materials, semiconductor devices, transparent displays, sensors, capacitors, transistors, and other electronic components, graphite and compounds linked to it are frequently employed. Numerous significant advancements have been made in various fields, including chemistry, materials, physics, biology, the environment, and energy, as a result of the remarkable features of graphene materials and its potential application value. Here are some examples:

Robot/Bionic prosthesis. Additionally, graphene may be utilized in the biomedical sector to enhance prosthetic limbs. People can sense muscle contractions and react to them by implanting graphene-based neural sensors into their limbs. They can better manage the robotic arm's power and

mobility thanks to this. In addition to being less heavy and non-intrusive, graphene reacts swiftly to pressure, enabling the wearer to move and control themselves naturally. Future prosthetics may be more responsive and comfortable than ever thanks to graphene.

Transparent touch display. Only 2.3% of light is absorbed by the extremely thin, nearly transparent graphene layer. However, it is so dense that not even the helium atoms, which are the smallest gas atoms, can pass through it. These qualities make it an excellent raw material for transparent electronic goods, including solar panels, light-emitting panels, and touch displays [15].

Graphene light bulb. Due to graphene's high conductivity, light bulbs can be utilized for extended periods of time while using 10% less energy. It is also less expensive and has a stronger construction than LED lights.

According to the analysis of use cases, gallium nitride is still more frequently employed than graphene right now. This might be in part due to graphene technology being less stable and developed than gallium nitride. Gallium nitride and other current semiconductor materials may be replaced in some ways by graphene, which has a wider range of application prospects because certain of its features are still more advanced than those of gallium nitride.

4. Conclusion

In summary, this article has undertaken a comprehensive analysis and comparison of gallium nitride and graphene, delving into their structural intricacies, diverse applications, and future prospects within the ever-evolving landscape of science and technology. These two remarkable materials are poised to play pivotal roles in various industries as advancements in these fields continue to unfold.

From a material perspective, graphene consistently emerges as the frontrunner in theoretical property comparisons, showcasing its immense potential for a wide array of applications. Its future prospects appear boundless, promising innovations across numerous sectors. On the other hand, gallium nitride, while perhaps not as universally versatile as graphene, finds its niche in power and wireless base stations, presenting a distinct set of advantages for specific applications.

Nonetheless, a common challenge shared by both graphene and gallium nitride is their prohibitively high cost, intricate production processes, and limited output. However, it is reasonable to anticipate that these obstacles will be surmounted in the foreseeable future, as research and development efforts intensify. Consequently, a growing spotlight is likely to be cast upon these two materials as their feasibility and scalability improve, positioning them as key players in the technological landscape of tomorrow. As science and engineering continue to advance, the significance of graphene and gallium nitride is poised to grow, prompting a heightened level of attention and exploration from both the scientific community and industry stakeholders alike.

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