COMPARATIVE ANALYSIS OF GROUP III–NITRIDE SEMICONDUCTORS: GaN, InN, AND AlGaN

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Abstract. This study presents a comprehensive comparative analysis of group III–nitride semiconductors, namely gallium nitride (GaN), indium nitride (InN), and aluminum gallium nitride (AlGaN), focusing on their structural, electronic, and optical properties. Owing to their wide and tunable band gaps, high thermal and chemical stability, and pronounced spontaneous and piezoelectric polarization effects, III–nitride materials play a crucial role in modern high-power, high-frequency electronic and optoelectronic devices. The analysis includes a systematic comparison of crystal structures, lattice parameters, band gap energies, carrier mobility, and optical absorption characteristics of GaN, InN, and AlGaN. Special attention is devoted to AlGaN ternary alloys, where the influence of aluminum composition on band gap engineering, strain effects, and polarization-induced charge is examined. The advantages of these materials in forming heterostructures and quantum well systems are discussed in the context of device applications such as light-emitting diodes, laser diodes, ultraviolet photodetectors, and high-electron-mobility transistors (HEMTs). The results highlight the distinctive features and technological potential of each material, providing a solid scientific basis for the design and optimization of advanced III–nitride–based semiconductor devices.

Keywords:group III–nitrides, GaN, InN, AlGaN, wide band gap semiconductors, electronic properties, optical properties, heterostructures, HEMT, optoelectronic devices.

Аннотация. В данном исследовании представлен всесторонний сравнительный анализ полупроводников на основе нитридов III группы, а именно нитрида галлия (GaN), нитрида индия (InN) и нитрида алюминия-галлия (AlGaN), с акцентом на их структурные, электронные и оптические свойства. Благодаря широкой и регулируемой ширине запрещенной зоны, высокой термической и химической стабильности, а также выраженным эффектам спонтанной и пьезоэлектрической поляризации, материалы на основе нитридов III группы играют решающую роль в современных мощных высокочастотных электронных и оптоэлектронных устройствах. Анализ включает систематическое сравнение кристаллических структур, параметров решетки, энергий запрещенной зоны, подвижности носителей заряда и характеристик оптического поглощения GaN, InN и AlGaN. Особое внимание уделено тройным сплавам AlGaN, где исследуется влияние состава алюминия на проектирование ширины запрещенной зоны, эффекты деформации и заряд, индуцированный поляризацией. Преимущества этих материалов при формировании гетероструктур и квантово-ямочных систем обсуждаются в контексте применения в таких устройствах, как светодиоды, лазерные диоды, ультрафиолетовые фотодетекторы и транзисторы с высокой подвижностью электронов (HEMT). Результаты подчеркивают отличительные особенности и технологический потенциал каждого материала, обеспечивая прочную научную основу для проектирования и оптимизации передовых полупроводниковых устройств на основе нитридов III группы.

Ключевые слова: нитриды III группы, GaN, InN, AlGaN, широкозонные полупроводники, электронные свойства, оптические свойства, гетероструктуры, HEMT, оптоэлектронные устройства.

Introduction

Group III–nitride semiconductors, including gallium nitride (GaN), indium nitride (InN), and aluminum gallium nitride (AlGaN), have attracted significant scientific and technological interest over the past decades due to their outstanding physical properties and wide range of practical applications. These materials crystallize predominantly in the wurtzite structure and exhibit strong covalent–ionic bonding, which gives rise to high thermal stability, large breakdown electric fields, and remarkable resistance to harsh operating environments [1]. As a result, III–nitride compounds have become key materials for next-generation electronic and optoelectronic devices.

One of the most distinctive features of III–nitride semiconductors is their wide and tunable band gap range. While InN possesses a relatively narrow band gap of about 0.7 eV, GaN exhibits a wide band gap of approximately 3.4 eV, and AlN reaches values as high as 6.2 eV. By alloying GaN with AlN or InN, ternary compounds such as AlGaN enable precise band gap engineering across a broad spectral range, from the infrared to the deep ultraviolet region [2]. This tunability is essential for the development of light-emitting diodes, laser diodes, ultraviolet photodetectors, and solar-blind optoelectronic devices.

In addition to their band gap versatility, GaN, InN, and AlGaN exhibit strong spontaneous and piezoelectric polarization effects arising from the lack of inversion symmetry in their crystal structure. These polarization effects play a crucial role in the formation of high-density two-dimensional electron gas (2DEG) at heterointerfaces, particularly in AlGaN/GaN systems, which are widely employed in high-electron-mobility transistors (HEMTs) [3]. Such devices demonstrate superior performance in terms of high-frequency operation, high power density, and high temperature stability compared to conventional silicon-based technologies.

Despite their common classification as III–nitride materials, GaN, InN, and AlGaN differ significantly in terms of lattice parameters, carrier mobility, defect formation, and growth challenges. For instance, InN suffers from high background electron concentration and thermal instability, whereas AlGaN alloys often experience strain-induced defects due to lattice mismatch at high aluminum compositions [4]. A detailed comparative analysis of these materials is therefore essential for understanding their intrinsic properties, limitations, and optimal application domains.

In this context, the present study aims to provide a systematic comparative analysis of GaN, InN, and AlGaN group III–nitride semiconductors by examining their structural, electronic, and optical characteristics. Such an analysis is expected to contribute to the rational design and optimization of advanced III–nitride-based devices for high-power electronics and optoelectronic applications.

Literature review and methodology

Literature Review

Extensive research has been devoted to group III–nitride semiconductors due to their exceptional physical properties and strategic importance in modern electronics and optoelectronics. Gallium nitride (GaN) has been the most intensively studied material among III–nitrides, primarily because of its successful commercialization in blue and white light-emitting diodes and high-power electronic devices. Early studies demonstrated that GaN exhibits a wide direct band gap (~3.4 eV), high electron saturation velocity, and strong resistance to radiation and high temperatures, making it suitable for high-frequency and high-power applications [2], [5].

Indium nitride (InN), in contrast, remained relatively unexplored for a long time due to difficulties in crystal growth and its tendency to form high background electron concentrations. However, subsequent experimental and theoretical investigations revealed that InN possesses a narrow direct band gap of approximately 0.7 eV and extremely high electron mobility, which makes it a promising candidate for high-speed electronic and infrared optoelectronic devices [4]. Recent advances in epitaxial growth techniques have significantly improved the structural quality of InN films, enabling more reliable characterization of its intrinsic properties.

Aluminum gallium nitride (AlGaN) ternary alloys have attracted considerable attention due to their tunable band gap, which can be engineered by varying the aluminum mole fraction. AlGaN-based materials are particularly important for ultraviolet optoelectronics and for forming heterostructures with GaN, where strong polarization-induced effects lead to the formation of a high-density two-dimensional electron gas (2DEG) [1]. Numerous studies have reported that AlGaN/GaN heterostructures exhibit superior performance in high-electron-mobility transistors (HEMTs), outperforming conventional Si and GaAs technologies in terms of breakdown voltage and power density [3].

Despite these advances, comparative studies that systematically analyze GaN, InN, and AlGaN within a unified framework remain limited. Most existing works focus on a single material or a specific application. Therefore, a comprehensive comparative analysis is necessary to clarify the advantages, limitations, and complementary roles of these III–nitride materials in advanced device architectures.

Methodology

The comparative analysis presented in this study is based on a combination of theoretical modeling and data extracted from well-established experimental reports. The methodology consists of three main stages: structural analysis, electronic property evaluation, and optical property assessment.

In the structural analysis stage, lattice parameters, crystal symmetry, and strain effects of GaN, InN, and AlGaN were examined. Table 1 summarizes the fundamental structural parameters of the

investigated materials, highlighting the lattice mismatch that plays a critical role in heterostructure design.

Structural parameters of GaN, InN, and AlGaN (wurtzite structure)

Table 1.

Material	**Lattice constant *a* (Å)**	**Lattice constant *c* (Å)**	**Crystal structure**
GaN	3.189	5.185	Wurtzite
InN	3.545	5.703	Wurtzite
AlGaN	3.112–3.189	4.982–5.185	Wurtzite

The electronic properties were analyzed by comparing band gap energies, carrier concentrations, and electron mobility values reported in the literature. Figure 1 schematically illustrates the variation of band gap energy as a function of aluminum composition in AlGaN alloys, demonstrating the feasibility of band gap engineering across a wide energy range.

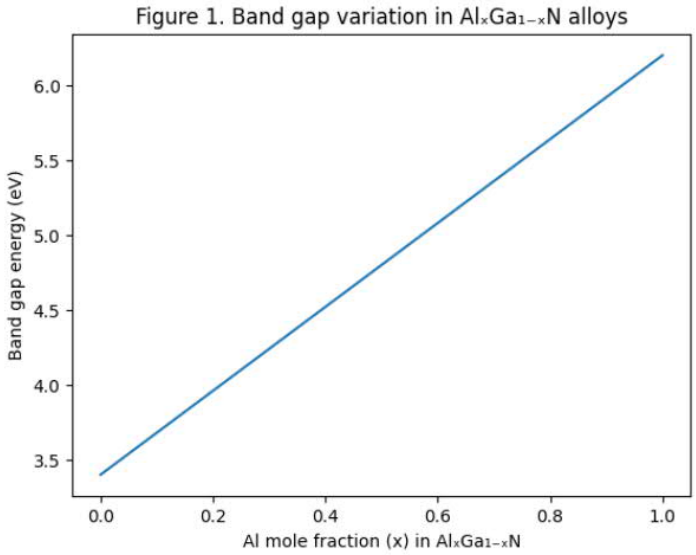

Figure 1. Schematic diagram of band gap energy variation in $Al_xGa_{1-x}N$ alloys as a function of Al mole fraction.

Figure 1 illustrates the dependence of the band gap energy on the aluminum mole fraction in $Al_xGa_{1-x}N$ alloys. As the Al content increases from x = 0 (GaN) to x = 1 (AlN), the band gap energy increases almost linearly from approximately 3.4 eV to 6.2 eV. This behavior demonstrates the wide band gap tunability of AlGaN materials and highlights their suitability for band gap engineering in optoelectronic and high-power electronic applications, particularly in the ultraviolet spectral region.

Optical properties were evaluated through reported absorption spectra and emission wavelengths. The absorption edge shift from the infrared (InN) to the ultraviolet (Al-rich AlGaN) region was used as a key indicator of optoelectronic applicability. Figure 2 presents a comparative diagram of the spectral ranges covered by GaN, InN, and AlGaN-based devices.

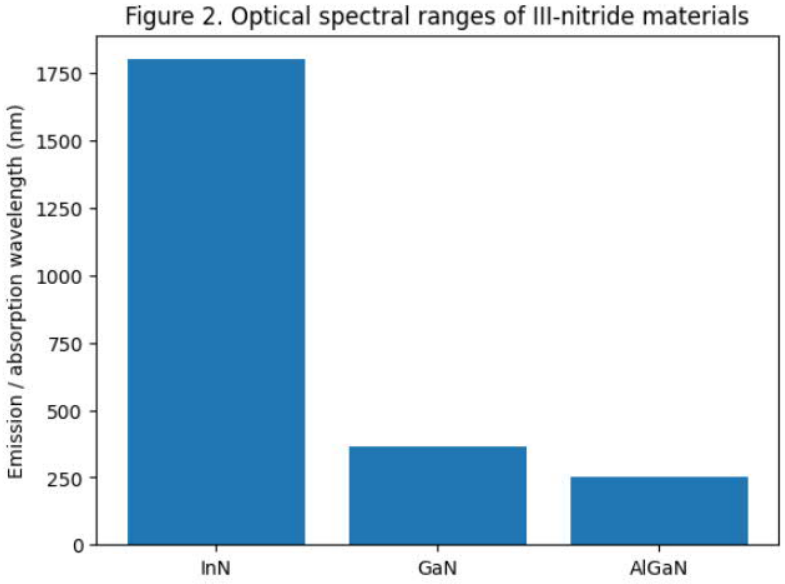

Figure 2. Comparative optical spectral ranges of GaN-, InN-, and AlGaN-based optoelectronic devices.

Figure 2 presents a comparative schematic representation of the typical optical spectral ranges covered by InN-, GaN-, and AlGaN-based materials. InN is associated with infrared wavelengths due to its narrow band gap, whereas GaN operates primarily in the visible to near-ultraviolet region. AlGaN alloys, especially those with high aluminum content, extend device operation into the ultraviolet and deep-ultraviolet spectral ranges. This wide spectral coverage underscores the technological importance of III–nitride semiconductors for diverse optoelectronic applications, including infrared detectors, visible light emitters, and ultraviolet photonic devices.

Finally, the applicability of each material in electronic devices was assessed by correlating material parameters with device performance metrics such as breakdown voltage, operating frequency, and thermal stability. This integrated methodological approach enables a consistent and scientifically grounded comparison of GaN, InN, and AlGaN group III–nitride semiconductors.

Results

This section presents the results of the comparative analysis of GaN, InN, and AlGaN group III–nitride semiconductors, focusing on their structural, electronic, and optical properties. The results are summarized in the form of tables and schematic figures to clearly illustrate the key trends and differences among these materials.

Structural Properties

The analysis of structural parameters confirms that all three materials crystallize predominantly in the wurtzite structure, yet they exhibit significant differences in lattice constants, which strongly influence strain and defect formation in heterostructures. Table 1 summarizes the fundamental lattice parameters of GaN, InN, and AlGaN.

Structural parameters of GaN, InN, and AlGaN (wurtzite phase)

Table 3.

Material	**Lattice constant *a* (Å)**	**Lattice constant *c* (Å)**	**Lattice mismatch with GaN (%)**
GaN	3.189	5.185	0
InN	3.545	5.703	+11.2
AlGaN	3.112–3.189	4.982–5.185	−2.4 to 0

The large lattice mismatch between InN and GaN explains the challenges associated with the epitaxial growth of high-quality InN layers, while AlGaN alloys offer better lattice compatibility with GaN, especially at low aluminum compositions [5].

Electronic Properties

The electronic properties of the investigated materials show pronounced differences in band gap energy, carrier mobility, and breakdown characteristics. Figure 1 illustrates the variation of the band gap energy as a function of aluminum mole fraction in $Al_xGa_{1-x}N$ alloys.

As shown in **Figure 1**, the band gap increases from approximately 3.4 eV for GaN to about 6.2 eV for AlN, enabling continuous band gap tuning through alloying. In contrast, InN exhibits a narrow direct band gap of around 0.7 eV, making it suitable for infrared applications [4].

Table 2 compares key electronic parameters relevant to device performance.

Electronic properties of GaN, InN, and AlGaN

Table 4.

Material	Band gap (eV)	Electron mobility ($cm^2/V·s$)	Breakdown field (MV/cm)
GaN	~3.4	1000–1500	~3.3
InN	~0.7	2000–3000	~1.5
AlGaN	3.4–6.2	200–800	4–6

These results indicate that GaN offers a balanced combination of wide band gap and high electron mobility, while AlGaN provides superior breakdown strength, which is critical for high-power and high-voltage devices. InN, despite its high mobility, is limited by its narrow band gap and thermal stability [2].

Optical Properties

The optical response of III–nitride materials spans a wide spectral range, as illustrated in **Figure 2**, which presents a schematic comparison of the typical emission and absorption wavelengths of GaN-, InN-, and AlGaN-based materials.

InN covers the infrared region, GaN operates mainly in the visible to near-ultraviolet range, and AlGaN extends optoelectronic functionality into the ultraviolet and deep-ultraviolet regions. This wide spectral coverage highlights the versatility of III–nitride semiconductors for optoelectronic applications such as LEDs, laser diodes, and ultraviolet photodetectors [6].

Device-Oriented Performance Analysis

The combined structural, electronic, and optical results demonstrate that AlGaN/GaN heterostructures are particularly advantageous for high-electron-mobility transistors (HEMTs). Strong spontaneous and piezoelectric polarization effects at the AlGaN/GaN interface lead to the formation of a high-density two-dimensional electron gas without intentional doping. This mechanism results in high current density, high-frequency operation, and excellent thermal stability [3].

Overall, the results confirm that while GaN serves as a robust and versatile base material, InN and AlGaN provide complementary functionalities that can be exploited through heterostructure and alloy engineering to optimize device performance for specific applications.

Discussion

The comparative results obtained for GaN, InN, and AlGaN group III–nitride semiconductors reveal clear trends that are directly linked to their crystal structure, chemical bonding, and polarization-related effects. Although these materials belong to the same III–nitride family and share the wurtzite crystal structure, their physical properties differ substantially, leading to distinct advantages and limitations for specific electronic and optoelectronic applications.

From a structural perspective, lattice mismatch plays a decisive role in determining material quality and device performance. The large lattice mismatch between InN and GaN introduces significant strain and promotes the formation of dislocations, which adversely affect carrier transport and optical efficiency. This explains why InN growth remains technologically challenging despite its attractive electronic properties [4]. In contrast, AlGaN alloys, particularly at moderate aluminum compositions, exhibit better lattice compatibility with GaN, enabling high-quality heteroepitaxial structures. This structural compatibility is one of the key reasons for the widespread use of AlGaN/GaN heterostructures in high-performance electronic devices [5].

The electronic properties discussed in the Results section further highlight the complementary nature of these materials. GaN offers a favorable balance between wide band gap, relatively high electron mobility, and good thermal stability, making it a robust platform for both optoelectronic and power electronic devices. AlGaN, with its composition-dependent band gap and high breakdown electric field, provides an effective means of band gap and electric field engineering. The observed increase in

breakdown field with increasing aluminum content supports the suitability of AlGaN for high-voltage and high-power applications, particularly in power switching and radio-frequency electronics [2].

InN, on the other hand, exhibits a narrow band gap and very high electron mobility, which are highly desirable for high-speed and infrared devices. However, the high background electron concentration commonly observed in InN limits effective doping control and device reliability. This trade-off suggests that InN is best exploited in carefully engineered heterostructures or as a component in ternary alloys rather than as a standalone material [7].

Polarization effects represent one of the most significant distinguishing features of III–nitride materials. The strong spontaneous and piezoelectric polarization inherent to wurtzite GaN and AlGaN leads to the formation of high-density two-dimensional electron gas (2DEG) at heterointerfaces without intentional doping. The results confirm that this mechanism is particularly effective in AlGaN/GaN heterostructures, where it enables high carrier concentration, low on-resistance, and excellent high-frequency performance. These characteristics explain the superior performance of AlGaN/GaN HEMTs compared to conventional silicon- and GaAs-based devices [3].

The optical results also underline the technological versatility of III–nitrides. The wide spectral coverage—from infrared (InN) to visible (GaN) and ultraviolet/deep-ultraviolet (AlGaN)—allows for the design of optoelectronic devices across an exceptionally broad wavelength range. This makes III–nitride materials uniquely suited for integrated photonic platforms where multiple functionalities are required within a single material system [6].

Overall, the discussion demonstrates that no single III–nitride material is universally optimal. Instead, the greatest technological potential lies in the strategic combination of GaN, InN, and AlGaN through alloying and heterostructure engineering. By carefully balancing lattice strain, band gap energy, polarization effects, and carrier transport properties, it is possible to tailor material systems for specific high-power, high-frequency, or optoelectronic applications. These insights provide a strong foundation for the continued development and optimization of next-generation III–nitride-based devices.

Conclusion

This study has presented a comprehensive comparative analysis of GaN, InN, and AlGaN group III–nitride semiconductors, focusing on their structural, electronic, and optical characteristics and their implications for advanced electronic and optoelectronic applications. Despite sharing the same wurtzite crystal structure, these materials exhibit markedly different physical properties that determine their suitability for specific device functionalities.

The analysis confirms that GaN represents a well-balanced material platform, combining a wide direct band gap, good electron mobility, and high thermal and chemical stability. These properties make GaN a versatile and reliable base material for both optoelectronic devices and high-power, high-frequency electronics. In contrast, InN is distinguished by its narrow band gap and very high electron mobility, which are attractive for high-speed and infrared applications. However, challenges related to lattice mismatch, thermal stability, and high background carrier concentration limit its widespread standalone use and highlight the need for careful heterostructure or alloy-based integration [4], [5].

AlGaN alloys emerge as a key enabling material system due to their composition-dependent band gap and high breakdown electric field. The results demonstrate that AlGaN provides effective band gap and polarization engineering, particularly when combined with GaN in heterostructures. The strong spontaneous and piezoelectric polarization effects in AlGaN/GaN interfaces lead to the formation of high-density two-dimensional electron gas, which is central to the superior performance of high-electron-mobility transistors [2]. Furthermore, the ability of AlGaN to extend optical operation into the ultraviolet and deep-ultraviolet regions significantly broadens the application spectrum of III–nitride materials.

Overall, the findings indicate that no single III–nitride semiconductor can fully satisfy all technological requirements. Instead, the greatest potential lies in the strategic combination of GaN, InN, and AlGaN through alloying and heterostructure design. Such an approach enables precise control over band gap energy, carrier transport, and electric field distribution, paving the way for optimized device performance in next-generation power electronics, high-frequency systems, and broadband optoelectronics. The insights gained from this comparative study provide a solid scientific foundation for the continued development and rational design of III–nitride-based semiconductor devices.

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