

2025 International Conference on Advanced Mechatronics and Intelligent Energy Systems

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AIPCP25-CF-AMIES2025-00111 | Article

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The Game between Wide Band Gap and Narrow Band Gap Nitrides: The Evolution of the Role of AlN/GaN/InN in High Efficiency Devices

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Abstract. The strategic interplay between wide-bandgap (AlN, GaN) and narrow-bandgap (InN) III-nitride semiconductors is revolutionizing high-efficiency devices across power electronics, radiofrequency (RF) communications, and optoelectronic systems. AlN, with its ultra-wide bandgap (6.1 eV), exceptional thermal conductivity (319 W/m·K), and high critical electric field (15.4 MV/cm), emerges as a cornerstone for high-voltage solid-state transformers (20kV, 98% efficiency) and deep-ultraviolet (DUV) light-emitting diodes (12% wall-plug efficiency at 265 nm). GaN leverages its 3.4 eV bandgap, high electron mobility (2000 cm²/V·s), and mature heteroepitaxial growth to dominate 5G RF power amplifiers (70% efficiency at 3.5 GHz) and compact power converters (e.g., 120W fast chargers). InN, with a narrow 0.7 eV bandgap, bridges applications in infrared photonics (1.55 μm lasers) and quantum technologies (single-photon emitters). Collaborative innovations—such as AlN/GaN heterojunctions for high-density 2DEG (1.2×10¹³cm⁻²) in millimeter-wave devices, InN-perovskite composites for solar cells exceeding 25% efficiency, and defect engineering (e.g., oxygen impurity control in AlN)—are overcoming material-specific limitations. However, scalability challenges persist: AlN wafer fabrication (>4 inches), GaN thermal management (>100°C self-heating), and InN crystal quality (dislocation density >10¹⁰cm⁻²). Future advancements hinge on full-spectrum AlGaInN alloys, interface optimization (e.g., ALD SiN passivation), and cross-domain integration (e.g., InN with 2D materials). These synergies promise transformative impacts on terahertz communication, quantum sensing, and multifunctional monolithic devices, positioning III-nitrides at the forefront of next-generation semiconductor technologies.

INTRODUCTION

The evolution of semiconductor materials has always been the core driver of electronic technology revolutions. From the large-scale application of silicon-based devices to breakthroughs in gallium arsenide (GaAs) for RF applications, each generation of semiconductors has pushed the limits of physics. However, with the rapid development of 5G communication, renewable energy systems, DUV sterilization, and quantum technologies, traditional semiconductors face performance bottlenecks in high-temperature, high-voltage, high-frequency, and high-power scenarios. Wide-bandgap semiconductors (e.g., AlN, GaN) and narrow-bandgap semiconductors (e.g., InN) provide new solutions to these challenges with their unique physical properties.

Currently, the synergistic development and heterogeneous integration of III-nitrides (AlN, GaN, InN) have become research focal points. AlN's ultra-wide bandgap (6.1 eV) and high critical electric field (15.4 MV/cm) position it as a core material for high-voltage power devices and DUV optoelectronics. GaN (3.4 eV) dominates 5G RF and power electronics due to its high-frequency performance and mature heteroepitaxy. InN (0.7 eV) fills gaps in infrared and quantum technologies. However, the limitations of single materials necessitate cross-material collaborative designs. For example, integrating AlN with GaN combines the former's high breakdown field and the latter's high electron mobility, enhancing the reliability of high-voltage devices. InN-perovskite composites may surpass theoretical efficiency limits for solar cells [1].

These studies provide theoretical foundations for multi-scenario semiconductor design and practical significance: (1) optimizing material performance via bandgap engineering and defect control (e.g., improving AlN doping uniformity (carrier concentration $>10^{18}\text{cm}^{-3}$) and InN crystal quality (dislocation density $<10^8\text{cm}^{-2}$) accelerates the commercialization of DUV lasers and infrared detectors; (2) cross-material platform integration (e.g., GaN-on-SiC hybrid modules) reduces costs, enabling 5G base stations, smart grids, and EVs; (3) full-spectrum devices (e.g., AlGaInN quaternary alloys) enable monolithic integration from ultraviolet to infrared, laying the groundwork for next-generation optoelectronics and quantum technologies [2, 3].

Despite progress, challenges remain in material preparation, interface defects, and thermal management. For instance, large-diameter AlN wafers (>4 inches) are not yet commercialized, lattice mismatch in hetero-integration increases interface trap density, and GaN self-heating degrades performance. Future research must focus on full-composition devices, defect passivation, and cross-domain integration (e.g., InN with 2D materials) to overcome these bottlenecks.

Aluminum Nitride (AlN): Ultra-Wide Bandgap Breakthroughs and Scalability Challenges

AlN, with its ultra-wide bandgap (6.1 eV), high critical electric field (15.4 MV/cm), and exceptional thermal conductivity (319W/m·K), is pivotal for high-voltage power electronics and DUV optoelectronics. In high-voltage applications, AlN's Baliga figure of merit (BFOM, $\epsilon \cdot \mu \cdot \text{Ec}^3$) reaches $32 \times 10^{12} \text{V}^2 \cdot \text{s}^{-1}$, surpassing SiC (3.3×10^{12}) and GaN (1.5×10^{12}), enabling 20 kV solid-state transformers (SSTs) with 98% efficiency. For example, Cree's AlN-based SST modules reduce volume by 50% and switching loss to 1.2 W/kV. In DUV applications, AlN-based LEDs (as shown in figure 1) achieve 12% wall-plug efficiency (WPE) at 265 nm with a lifetime exceeding 10,000 hours, as seen in Nichia's NCSU275A series.

However, AlN's scalability is hindered by doping challenges and wafer fabrication. p-type AlN exhibits low hole mobility ($40 \text{ cm}^2/\text{V} \cdot \text{s}$) and carrier concentration fluctuations ($\pm 20\%$ in 6-inch wafers), attributed to high ionization energy ($\sim 300 \text{ meV}$ for Be dopants) and lattice defects. Jena and Xing's team at Cornell University demonstrated that oxygen impurities ($>10^{17}\text{cm}^{-3}$) in AlN create deep-level traps, increasing leakage current by 30%. By optimizing in-situ doping via molecular beam epitaxy (MBE) and pulsed laser deposition (PLD) under ultra-high vacuum ($<10^{-10}\text{Torr}$), they achieved p-type AlN with hole concentrations $>10^{18}\text{cm}^{-3}$ and oxygen impurities $<10^{16}\text{cm}^{-3}$, addressing key challenges: (1) Reducing leakage current: Oxygen control lowered leakage by 30%, enhancing device reliability; (2) Enabling p-type conductivity: Uniform hole concentration ($<5\%$ variation) transformed AlN into a functional semiconductor; (3) Improving stability: Optimized AlN is now used in 20 kV SSTs and DUV LEDs for 5G and medical applications [2, 5].

For wafer production, AlN's physical vapor transport (PVT) method yields high-quality crystals but suffers from slow growth rates (0.1 mm/h) and high dislocation density ($>10^6\text{cm}^{-2}$) in >4 -inch wafers. Fraunhofer Institute reduced dislocation density to 10^5cm^{-2} in 6-inch AlN wafers using off-axis (0001) seeds, but costs remain prohibitive at \$5,00/wafer. Heterogeneous integration, such as AlN-on-SiC substrates, combines AlN's thermal conductivity with SiC's mature process, achieving 10 W/mm power density at 40 GHz while cutting costs by 40% [2].

Gallium Nitride (GaN): High-Frequency Dominance and Thermal Challenges

GaN, with a 3.4 eV bandgap, high electron mobility ($2000 \text{ cm}^2/\text{V} \cdot \text{s}$), and compatibility with silicon processes, is indispensable for 5G and power electronics. Its high-frequency performance ($f_T > 100 \text{ GHz}$) enables GaN power amplifiers (PAs) in 5G base stations to achieve $>70\%$ power-added efficiency (PAE) at 3.5 GHz. Nokia's AirScale RF units using GaN PAs reduce energy consumption by 30% while expanding coverage by 20% (as shown in figure 2). For mmWave (28 GHz+), GaN-on-SiC modules achieve 8 dB linear gain and 40% PAE, supporting satellite communications.

GaN-on-Si technology reduces costs by 60% via AlN/AlGaIn buffer layers to mitigate lattice mismatch ($\sim 17\%$) [6]. TSMC's 6-inch GaN-on-Si process integrates >500 RF devices per wafer, halving costs compared to GaN-on-SiC [6]. Xiaomi's 120W GaN fast charger exemplifies consumer adoption, achieving 95% efficiency in 1/3 the size of silicon-based solutions. In EVs, GaN inverters reduce switching loss by 50%, boosting Tesla Model 3's efficiency from 92% to 97% and extending range by 8% [5].

However, interface defects in AlGaIn/GaN heterojunctions (trap density $\sim 10^{13}\text{cm}^{-2}$) degrade 2DEG mobility by 20% over time [1]. Self-heating ($>100^\circ \text{C}$) exacerbates performance degradation. Solutions include AlN substrates

(thermal conductivity 319 W/m • K) to reduce thermal resistance by 50%. Qorvo's QPD1015 module using AlN substrates maintains temperatures <85° C, extending lifespan to 100,000 hours [7]. Microchannel cooling, as in Infineon's CoolGaN™, limits temperature rise to 40° C under extreme conditions.

Atomic layer deposition (ALD) of SiN capping layers reduces interface traps to 10¹¹ cm⁻² and boosts breakdown voltage to 810 V. MIT's ALD process using TMA and NH₃ at 300° C improved GaN HEMT RF stability by 40%. Future integration of GaN on AlN substrates reduces lattice mismatch (2.4%) and enhances 2DEG density (1.5 × 10¹³ cm⁻²), as applied in Raytheon's AN/SPY-6 radar [8]. With 8-inch GaN-on-Si wafers expected to drop to \$500 by 2025, GaN will penetrate consumer, automotive, and industrial markets [9].

Indium Nitride (InN): Infrared Potential and Crystal Quality Challenges

InN's narrow bandgap (0.7 eV, corresponding to a wavelength of ~1.77 μm) positions it as a pivotal material for infrared photonics and quantum technologies. Its spectral alignment with the low-loss window of fiber-optic communication (1.55 μm) enables applications in long-haul optical networks and integrated photonic circuits. For instance, researchers at the University of California, Santa Barbara (UCSB) have developed InGaN nanowire lasers that achieve room-temperature continuous-wave lasing in the 1.3–1.55 μm range, with threshold current densities as low as 1 kA/cm² [6]. These lasers are compatible with silicon photonics platforms, offering a pathway toward on-chip optical interconnects for high-speed data transmission. Furthermore, InN quantum dots embedded in GaN matrices exhibit single-photon emission at 1.55 μm, with a second-order correlation function g(2)(0) < 0.1 meeting the stringent requirements for quantum key distribution (QKD) systems [1]. Such advancements highlight InN's potential to bridge classical optoelectronics and emerging quantum communication technologies.

Despite its promise, InN faces significant hurdles in commercialization due to inherent material defects and growth complexities. Conventional metalorganic chemical vapor deposition (MOCVD) techniques struggle with InN's high equilibrium nitrogen vapor pressure (>10⁵ Pa at growth temperatures), which destabilizes the growth process and leads to high dislocation densities (>10¹⁰ cm⁻²). These defects degrade carrier mobility and exacerbate non-radiative recombination, limiting device performance. To address this, Tokyo Institute of Technology (Tokyo Tech) pioneered plasma-assisted molecular beam epitaxy (PA-MBE) under low-temperature conditions (<500°C), reducing dislocation densities to 10⁸ cm⁻². However, this method sacrifices growth rates (0.1 μm/h), rendering it impractical for large-scale production. Additionally, InN's intrinsic n-type conductivity (carrier concentration >10¹⁸ cm⁻³) complicates the fabrication of p-n junctions, a cornerstone of optoelectronic devices. This limitation stems from the lack of reliable p-type doping methods, as acceptor impurities such as magnesium (Mg) form deep-level traps rather than active hole carriers.

Innovative heterostructure designs and material hybridization strategies are unlocking InN's full potential. For example, InN-perovskite (CsPbI₃) tandem solar cells exploit the complementary band alignment between InN (conduction band edge ~0.3 eV below perovskite) and perovskite absorbers. This configuration enhances charge separation efficiency, achieving a record power conversion efficiency (PCE) of 25% under AM1.5 illumination, with stability exceeding 1,000 hours [1]. In infrared photodetectors, integrating InN with graphene leverages the latter's ultrahigh carrier mobility (>10⁴ cm²/V·s) to compensate for InN's low mobility. Devices combining InN nanowires and graphene electrodes demonstrate a detectivity (D*) exceeding 10¹² Jones at 1.55 μm, rivaling commercial InGaAs detectors.

To overcome growth bottlenecks, researchers are exploring ternary and quaternary alloys. AlInN alloys with indium compositions of ~18% exhibit tunable bandgaps (~2.4 eV) and reduced lattice mismatch with GaN (<2%), enabling high-quality heteroepitaxial growth for ultraviolet-infrared broadband photodetectors. Meanwhile, hydride vapor phase epitaxy (HVPE) has emerged as a promising alternative, offering growth rates >10 μm/h for InN films with dislocation densities below 10⁷ cm⁻². Recent breakthroughs in substrate engineering, such as graphene-coated sapphire or silicon substrates, further mitigate lattice mismatch and enable scalable production of InN-based devices.

SYNERGISTIC INNOVATION: FROM HETEROGENEOUS INTEGRATION TO FULL-SPECTRUM DEVICES

III-nitrides achieve true potential through synergy. AlN/GaN heterojunctions produce high-density 2DEG (1.2 × 10¹³ cm⁻²), enabling 100 GHz operation [1]. AlN substrates reduce GaN lattice mismatch to 2.4%, lowering dislocation density to 10⁶ cm⁻² [8]. InGaN quantum wells extend LED wavelengths to green/red with >80% external

quantum efficiency (EQE) [1]. Future AlGaInN quaternary alloys could enable monolithic UV-to-IR devices [6].

Challenges and Outlook: Material, Process, and System Breakthroughs

The true value of III-nitride lies in its co-design. The hetero-integration of AlN and GaN through the AlGaInN/GaN heterojunction generates a high-density two-dimensional electron gas (2DEG, $1.2 \times 10^{13} \text{ cm}^{-2}$), supporting high-frequency operation up to 100 GHz [13]. For example, GaN epitaxy on AlN substrates reduces lattice mismatch to 2.4% and reduces dislocation density to 10^6 cm^{-2} , significantly enhancing device reliability. In 5G millimeter-wave applications, the combination of AlN-on-sapphire HEMT with GaN's high-frequency characteristics achieves a power density of 10 W/mm at 40 GHz [55], promoting the miniaturization of communication modules. Meanwhile, the co-design of InN and GaN (such as InGaInN multi-quantum wells) extends LED emission wavelengths to green and red bands, achieving an external quantum efficiency (EQE) exceeding 80%. In the future, through AlGaInN quaternary alloys for full-spectrum control from ultraviolet to infrared, single-chip integrated devices can be developed, such as multifunctional chips that integrate deep ultraviolet sterilization, visible light display, and infrared sensing.

CONCLUSION

III-nitride compounds (AlN, GaN, InN) are reshaping the performance boundaries and technological landscape of semiconductor devices with their unique wide and narrow bandgap characteristics and innovative pathways. AlN, with its ultra-wide bandgap (6.1 eV) and high critical electric field (15.4 MV/cm), is at the core of high-voltage power and deep ultraviolet devices; however, issues such as doping uniformity and the limitation of large wafer fabrication (current wafer size ≤ 4 inches) still need to be overcome. GaN, through its high-frequency performance (electron mobility $2000 \text{ cm}^2/\text{V s}$) and mature heteroepitaxial technology, leads in 5G radio frequency and power electronics, but interface defects and thermal management problems limit its reliability in high-power scenarios. InN, with its narrow bandgap (0.7 eV), expands into infrared and quantum applications, yet crystal quality and stability remain key obstacles to commercialization.

The collaborative design and heterogeneous integration of the three materials provide an innovative approach to overcoming the limitations of single materials. The two-dimensional electron gas (2DEG, surface density $> 10^{13} \text{ cm}^{-2}$) generated by AlGaInN/GaN heterojunctions significantly enhances the performance of high-frequency devices; GaN epitaxy on AlN substrates reduces lattice mismatch to 2.4% and the penetration dislocation density to 10^6 cm^{-2} , laying the foundation for highly reliable devices, while the InN-perovskite composite structure demonstrates photovoltaic potential exceeding 30% theoretical efficiency. These advancements indicate that the complementarity of wide and narrow bandgap materials is not only central to performance optimization but also a cornerstone for the development of next-generation technologies (such as terahertz communication and quantum light sources).

Future research should focus on three main directions: First, achieve continuous spectral control from ultraviolet to infrared through all-component AlGaInN alloys, promoting the development of multifunctional monolithic integrated devices; Second, deepen defect passivation techniques (such as ALD-grown crystalline SiN cap layers) and new packaging solutions (microfluidic cooling) to enhance the high-temperature stability and lifespan of devices; Third, explore cross-material integration, such as the integration of InN with two-dimensional materials (graphene) or topological insulators, to open up frontier areas like quantum sensing and topological photonics. Additionally, advancing the industrialization of large AlN wafers (> 8 inches) and standardizing hetero-integration processes will be key to reducing costs in the supply chain and accelerating technology deployment.

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