


III-Nitride Materials: Properties, Growth, and Applications

Yangfeng Li 

Changsha Semiconductor Technology and Application Innovation Research Institute, College of Semiconductors (College of Integrated Circuits), Hunan University, Changsha 410082, China; liyangfeng12@mailsucas.ac.cn

1. Introduction

Since the activation of magnesium (Mg) in p-type gallium nitride (GaN) [1,2], striking progress has been made in III-nitride materials in terms of properties, growth, and applications [3]. Nowadays, aluminum nitride (AlN) epitaxially grown on nano-patterned AlN/sapphire template has a lower dislocation density as low as $3.3 \times 10^4 \text{ cm}^{-2}$ [4–6]. The behavior of impurities such as carbon in GaN has also been thoroughly investigated [7]. Recently, methods for characterizing the edge dislocation density of a thin film [8] or the interface roughness of multiple quantum wells (MQWs) or superlattice structures have also been further developed [9]. In addition, the light emission mechanisms of InGaN have also been investigated through the clarification of localized states [10] and the direct observation of carrier transportation between different localized states [11,12]. Some mechanisms still need to be unveiled, such as the abnormal enhancement of photoluminescence (PL) intensity in the mid-temperature range of InGaN materials during the temperature-dependent photoluminescence (TDPL) measurement [13–18].

Due to their high luminous efficiency and widely tunable bandgap, InGaN light-emitting diodes (LEDs) have permeated our daily lives. The properties of InGaN LEDs are still being improved, such as the light-output power, the lower leakage current, the efficiency of green, yellow, orange, red, and ultraviolet LEDs, etc. [19–27]. The external quantum efficiency (EQE) of InGaN blue LEDs is over 80% [28], while that of green ones surpasses 50% [29,30]. Great breakthroughs are also made in the “green gap” range [31]. Novel treatments of the quantum barrier have also rendered thrilling properties [32–35]. Single-chip white light has also been investigated [36]. In recent years, with their merits of high brightness, fast response, and high resolution, microLEDs have played an important role in next-generation displays such as augmented reality, full-color matrix automotive lamps, pico-projectors, etc. [30,37–42]. The EQE of InGaN red microLEDs has already reached 7.4%, demonstrating promise for application soon [43,44]. Blue and green InGaN lasers have also achieved inspiring performances [45,46]. Photonic integrated circuits with lower power consumption may alleviate the heat dissipation problem in computers. Microdisk lasers are promising light sources in photonic integrated circuits [47]. The threshold, quality, and other properties are gradually being improved [47–52].

Owing to the polarization effect, two-dimensional electron gas (2DEG) can be generated adjacent to the AlGaN/GaN interface, thus facilitating the development of high-electron-mobility transistors (HEMTs) [53]. The enhancement-mode (i.e., normally off) GaN HEMT has been demonstrated by fluoride-based plasma treatment for the first time [54]. Nowadays, the p-GaN gate is more commonly used to obtain enhancement-mode GaN HEMTs [55]. At present, p-channel GaN field effect transistors (FETs) are attracting attention, with potential in fabricating GaN-based complementary integrated circuits [56–59].

Benefiting from the inverted polarization field, N-polar GaN may surmount the bottlenecks faced by their incumbent Ga-polar counterparts [60,61]. Achievements have been made in the metal–organic chemical vapor deposition (MOCVD) growth of N-polar GaN [62–66]. Additionally, HEMTs based on N-polar GaN have exhibited transcendental performance in some aspects [67–69].



Citation: Li, Y. III-Nitride Materials: Properties, Growth, and Applications. *Crystals* **2024**, *14*, 390. <https://doi.org/10.3390/cryst14050390>

Received: 10 April 2024

Accepted: 22 April 2024

Published: 23 April 2024



Copyright: © 2024 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

This Special Issue has collected recent research focused on the properties, growth, and applications of III-nitride materials. It contains ten articles and two reviews, which will be briefly described in the following paragraphs.

2. An Overview of Published Articles

Li et al.'s article (contribution 1) used an intelligent algorithm to investigate the light extraction surface structure for deep-ultraviolet LEDs (DUV-LEDs). As a result, compared to conventional structures, the optimized truncated pyramid array (TPA) and truncated cone array (TCA) structures enhanced the light extraction efficiency (LEE) of the DUV LED with an emission wavelength of 280 nm by 221% and 257%, respectively.

Chen et al. (contribution 2) investigated the surface evolution and emission properties of InGaN/GaN MQWs with different ammonia flow rates by MOCVD. Different ammonia flow rates led to different temperature-dependent photoluminescence (TDPL) behaviors. Combined with atomic force microscopy (AFM), the underlying mechanisms were investigated in detail.

The third article (contribution 3) was composed by Tian et al., who investigated GaN/MoS₂ heterostructures by first-principles calculations. The heterojunctions of N-polarity GaN/MoS₂ and Ga-polarity GaN/MoS₂ are compared from the binding energy. A type-II energy band alignment occurs between both the Ga-polarity and N-polarity GaN/MoS₂ polar heterojunctions, although the directions of the built-in electric field are opposite. Moreover, the energy band alignment could change from type II to type I by exerting in-plane biaxial strains on GaN/MoS₂ heterostructures.

The fourth article (contribution 4) by N'Dohi et al. investigated the physical and electrical properties of vertical GaN Schottky diodes. The correlation between the reverse leakage current and doping, as well as dislocations, was investigated.

Zhang et al. (contribution 5) fabricated a normally off p-GaN gate HEMT with an air-bridge source connection. The as-fabricated HEMT exhibited an on-resistance as low as 36 Ω·m, a threshold voltage of 1.8 V, a maximum drain current of 240 mA/mm, and a breakdown voltage of 715 V.

In the sixth article (contribution 6), Guo et al. quantitatively analyzed the relationship between carrier energy and the potential height to be surmounted in the GaAs/InGaAs MQW structure by considering the Heisenberg uncertainty principle. Pump-probe technology is adopted to determine the lifetime of the photo-generated carriers under short circuit (SC) and open circuit (OC) conditions.

Liu et al. (contribution 7) employed plasma-enhanced atomic layer deposition (PEALD) to grow aluminum nitride (AlN) thin films on Si (100), Si (111), and c-plane sapphire substrates at a low temperature of 250 °C. The as-grown polycrystalline AlN thin films had a hexagonal wurtzite structure with a preferred c-axis orientation regardless of the substrate. The surface morphology and refractive index were compared between the three samples and the mechanisms behind it were discussed.

Mukhopadhyay et al. (contribution 8) reported a crack-free AlGaIn/AlN/GaN HEMT structure with a high aluminum composition (>35%) and thick barrier (>30 nm) grown on sapphire substrate. It exhibited ultra-low sheet resistivity (<250 Ω/□). The optimized growth conditions were detailed. The density of 2DEG was as high as $1.46 \times 10^{13} \text{ cm}^{-2}$ and the mobility reached 1710 cm²/V·s at room temperature.

The ninth article (contribution 9) also comes from Mukhopadhyay et al., who prepared carbon-doped semi-insulating N-polar GaN on a sapphire substrate through a propane precursor. As N-polar GaN usually contains more oxygen than its Ga-polar counterparts, thus resulting in a high unintentionally doped electron concentration, this work provides a feasible method to grow semi-insulating N-polar GaN.

In Zhang et al.'s article (contribution 10), InGaIn-based red microLEDs (μLEDs) of different sizes were prepared. The KOH wet treatment was investigated to alleviate the surface damage to sidewalls after dry etching. It could significantly inhibit the surface non-

radiative recombination processes, thus enhancing the optical and electrical performances of the 5 μm μLEDs .

Han et al. (contribution 10) reviewed the research progress and development prospects of enhanced GaN HEMTs. The importance and merits of Si-based GaN HEMTs were illustrated. The MOCVD growth technology, HEMT structures, reliability, and CMOS compatibility were delineated and compared. Future development directions were also envisioned.

The twelfth text is also a review by Jafar et al. (contribution 12) on the growth conditions and EQEs of InGaN LEDs. The challenges of InGaN growth were reviewed. The mechanisms behind the efficiency droop were analyzed. Furthermore, novel approaches to improve the EQE were also discussed.

3. Conclusions

This compilation of articles is devoted to the growth, device fabrication, and theoretical calculations of III-nitride materials and structures. DUV LEDs, green lasers, red microLEDs, HEMTs, the low-temperature growth of III-nitride by PEALD, N-polar GaN, the heterostructure of GaN/MoS₂, vertical GaN Schottky diodes, and the mechanism of carrier transportation in multiple quantum wells are investigated by researchers globally. All the studies are important issues in the realm of III-nitride materials and applications. We hope the methods and results in this Special Issue will promote the exploration of III-nitride materials and applications, which keep providing discoveries that will change our daily lives.

Conflicts of Interest: The author declares no conflicts of interest.

List of Contributions

1. Li, Z.; Lu, H.; Wang, J.; Zhu, Y.; Yu, T.; Tian, Y. Maximizing the Light Extraction Efficiency for AlGaIn-Based DUV-LEDs with Two Optimally Designed Surface Structures under the Guidance of PSO. *Crystals* **2022**, *12*, 1700. <https://doi.org/10.3390/cryst12121700>.
2. Chen, Z.; Liang, F.; Zhao, D.; Yang, J.; Chen, P.; Jiang, D. Investigation into the MOCVD Growth and Optical Properties of InGaIn/GaN Quantum Wells by Modulating NH₃ Flux. *Crystals* **2023**, *13*, 127. <https://doi.org/10.3390/cryst13010127>.
3. Tian, F.; Kong, D.; Qiu, P.; Liu, H.; Zhu, X.; Wei, H.; Song, Y.; Chen, H.; Zheng, X.; Peng, M. Polarization Modulation on Charge Transfer and Band Structures of GaN/MoS₂ Polar Heterojunctions. *Crystals* **2023**, *13*, 563. <https://doi.org/10.3390/cryst13040563>.
4. N'Dohi, A.J.E.; Sonnevile, C.; Saidi, S.; Ngo, T.H.; De Mierry, P.; Frayssinet, E.; Cordier, Y.; Phung, L.V.; Morancho, F.; Maher, H.; et al. Micro-Raman Spectroscopy Study of Vertical GaN Schottky Diode. *Crystals* **2023**, *13*, 713. <https://doi.org/10.3390/cryst13050713>.
5. Zhang, Y.; Ding, G.; Wang, F.; Yu, P.; Feng, Q.; Yu, C.; He, J.; Wang, X.; Xu, W.; He, M.; et al. Normally-Off p-GaN Gate High-Electron-Mobility Transistors with the Air-Bridge Source-Connection Fabricated Using the Direct Laser Writing Grayscale Photolithography Technology. *Crystals* **2023**, *13*, 815. <https://doi.org/10.3390/cryst13050815>.
6. Guo, J.; Liu, W.; Ding, D.; Tan, X.; Zhang, W.; Han, L.; Wang, Z.; Gong, W.; Li, J.; Zhai, R.; et al. Analysis of Photo-Generated Carrier Escape in Multiple Quantum Wells. *Crystals* **2023**, *13*, 834. <https://doi.org/10.3390/cryst13050834>.
7. Liu, S.; Li, Y.; Tao, J.; Tang, R.; Zheng, X. Structural, Surface, and Optical Properties of AlN Thin Films Grown on Different Substrates by PEALD. *Crystals* **2023**, *13*, 910. <https://doi.org/10.3390/cryst13060910>.
8. Mukhopadhyay, S.; Liu, C.; Chen, J.; Tahmidul Alam, M.; Sanyal, S.; Bai, R.; Wang, G.; Gupta, C.; Pasayat, S.S. Crack-Free High-Composition (>35%) Thick-Barrier (>30 nm) AlGaIn/AlN/GaN High-Electron-Mobility Transistor on Sapphire with Low Sheet

- Resistance ($<250 \Omega/\square$). *Crystals* **2023**, *13*, 1456. <https://doi.org/10.3390/cryst13101456>.
9. Mukhopadhyay, S.; Sanyal, S.; Wang, G.; Gupta, C.; Pasayat, S.S. First Demonstration of Extrinsic C-Doped Semi-Insulating N-Polar GaN Using Propane Precursor Grown on Miscut Sapphire Substrate by MOCVD. *Crystals* **2023**, *13*, 1457. <https://doi.org/10.3390/cryst13101457>.
 10. Zhang, S.; Fan, Q.; Ni, X.; Tao, L.; Gu, X. Study on the Influence of KOH Wet Treatment on Red μ LEDs. *Crystals* **2023**, *13*, 1611. <https://doi.org/10.3390/cryst13121611>.
 11. Han, L.; Tang, X.; Wang, Z.; Gong, W.; Zhai, R.; Jia, Z.; Zhang, W. Research Progress and Development Prospects of Enhanced GaN HEMTs. *Crystals* **2023**, *13*, 911. <https://doi.org/10.3390/cryst13060911>.
 12. Jafar, N.; Jiang, J.; Lu, H.; Qasim, M.; Zhang, H. Recent Research on Indium-Gallium-Nitride-Based Light-Emitting Diodes: Growth Conditions and External Quantum Efficiency. *Crystals* **2023**, *13*, 1623. <https://doi.org/10.3390/cryst13121623>.

References

1. Amano, H.; Kito, M.; Hiramatsu, K.; Akasaki, I. P-Type Conduction in Mg-Doped GaN Treated with Low-Energy Electron Beam Irradiation (LEEBI). *Jpn. J. Appl. Phys.* **1989**, *28*, L2112–L2114. [[CrossRef](#)]
2. Nakamura, S.; Mukai, T.; Senoh, M.; Iwasa, N. Thermal Annealing Effects on P-Type Mg-Doped GaN Films. *Jpn. J. Appl. Phys.* **1992**, *31*, L139–L142. [[CrossRef](#)]
3. Nakamura, S.; Mukai, T.; Senoh, M. Candela-class high-brightness InGaN/AlGaIn double-heterostructure blue-light-emitting diodes. *Appl. Phys. Lett.* **1994**, *64*, 1687–1689. [[CrossRef](#)]
4. Wang, J.; Xie, N.; Xu, F.; Zhang, L.; Lang, J.; Kang, X.; Qin, Z.; Yang, X.; Tang, N.; Wang, X.; et al. Group-III nitride heteroepitaxial films approaching bulk-class quality. *Nat. Mater.* **2023**, *22*, 853–859. [[CrossRef](#)] [[PubMed](#)]
5. Shen, J.; Yang, X.; Liu, D.; Cai, Z.; Wei, L.; Xie, N.; Xu, F.; Tang, N.; Wang, X.; Ge, W.; et al. High quality AlN film grown on a nano-concave-circle patterned Si substrate with an AlN seed layer. *Appl. Phys. Lett.* **2020**, *117*, 022103. [[CrossRef](#)]
6. Wang, J.; Xu, F.; Liu, B.; Lang, J.; Zhang, N.; Kang, X.; Qin, Z.; Yang, X.; Wang, X.; Ge, W.; et al. Control of dislocations in heteroepitaxial AlN films by extrinsic supersaturated vacancies introduced through thermal desorption of heteroatoms. *Appl. Phys. Lett.* **2021**, *118*, 162103. [[CrossRef](#)]
7. Wu, S.; Yang, X.; Zhang, H.; Shi, L.; Zhang, Q.; Shang, Q.; Qi, Z.; Xu, Y.; Zhang, J.; Tang, N.; et al. Unambiguous Identification of Carbon Location on the N Site in Semi-insulating GaN. *Phys. Rev. Lett.* **2018**, *121*, 145505. [[CrossRef](#)] [[PubMed](#)]
8. Li, Y.; Yan, S.; Hu, X.; Song, Y.; Deng, Z.; Du, C.; Wang, W.; Ma, Z.; Wang, L.; Jia, H.; et al. Characterization of edge dislocation density through X-ray diffraction rocking curves. *J. Cryst. Growth* **2020**, *551*, 125893. [[CrossRef](#)]
9. Li, Y.; Die, J.; Yan, S.; Deng, Z.; Ma, Z.; Wang, L.; Jia, H.; Wang, W.; Jiang, Y.; Chen, H. Characterization of periodicity fluctuations in InGaN/GaN MQWs by the kinematical simulation of X-ray diffraction. *Appl. Phys. Express* **2019**, *12*, 045502. [[CrossRef](#)]
10. Zhu, Y.; Lu, T.; Zhou, X.; Zhao, G.; Dong, H.; Jia, Z.; Liu, X.; Xu, B. Origin of huge photoluminescence efficiency improvement in InGaN/GaN multiple quantum wells with low-temperature GaN cap layer grown in N_2/H_2 mixture gas. *Appl. Phys. Express* **2017**, *10*, 061004. [[CrossRef](#)]
11. Li, Y.; Deng, Z.; Ma, Z.; Wang, L.; Jia, H.; Wang, W.; Jiang, Y.; Chen, H. Visualizing carrier transitions between localization states in a InGaN yellow–green light-emitting–diode structure. *J. Appl. Phys.* **2019**, *126*, 095705. [[CrossRef](#)]
12. Li, Y.; Li, Y.; Zhang, J.; Wang, Y.; Li, T.; Jiang, Y.; Jia, H.; Wang, W.; Yang, R.; Chen, H. Direct Observation of Carrier Transportation between Localized States in InGaN Quantum Wells. *Crystals* **2022**, *12*, 1837. [[CrossRef](#)]
13. Ma, J.; Ji, X.; Wang, G.; Wei, X.; Lu, H.; Yi, X.; Duan, R.; Wang, J.; Zeng, Y.; Li, J.; et al. Anomalous temperature dependence of photoluminescence in self-assembled InGaN quantum dots. *Appl. Phys. Lett.* **2012**, *101*, 131101. [[CrossRef](#)]
14. Lu, T.; Ma, Z.; Du, C.; Fang, Y.; Wu, H.; Jiang, Y.; Wang, L.; Dai, L.; Jia, H.; Liu, W.; et al. Temperature-dependent photoluminescence in light-emitting diodes. *Sci. Rep.* **2014**, *4*, 6131. [[CrossRef](#)] [[PubMed](#)]
15. Liu, W.; Zhao, D.G.; Jiang, D.S.; Chen, P.; Liu, Z.S.; Zhu, J.J.; Shi, M.; Zhao, D.M.; Li, X.; Liu, J.P.; et al. Localization effect in green light emitting InGaN/GaN multiple quantum wells with varying well thickness. *J. Alloys Compd.* **2015**, *625*, 266–270. [[CrossRef](#)]
16. Weng, G.-E.; Zhao, W.-R.; Chen, S.-Q.; Akiyama, H.; Li, Z.-C.; Liu, J.-P.; Zhang, B.-P. Strong localization effect and carrier relaxation dynamics in self-assembled InGaN quantum dots emitting in the green. *Nanoscale Res. Lett.* **2015**, *10*, 31. [[CrossRef](#)] [[PubMed](#)]
17. Yang, J.; Zhao, D.G.; Jiang, D.S.; Chen, P.; Zhu, J.J.; Liu, Z.S.; Le, L.C.; Li, X.J.; He, X.G.; Liu, J.P.; et al. Optical and structural characteristics of high indium content InGaN/GaN multi-quantum wells with varying GaN cap layer thickness. *J. Appl. Phys.* **2015**, *117*. [[CrossRef](#)]
18. Li, Y.; Jin, Z.; Han, Y.; Zhao, C.; Huang, J.; Tang, C.W.; Wang, J.; Lau, K.M. Surface morphology and optical properties of InGaN quantum dots with varying growth interruption time. *Mater. Res. Express* **2019**, *7*, 015903. [[CrossRef](#)]
19. Li, Y.; Yang, R.; Jiang, Y.; Jia, H.; Wang, W.; Chen, H. In Situ AlGaIn Interlayer for Reducing the Reverse Leakage Current of InGaN Light-Emitting Diodes. *IEEE Electron. Device Lett.* **2023**, *44*, 777–780. [[CrossRef](#)]

20. Jiang, Y.; Li, Y.; Li, Y.; Deng, Z.; Lu, T.; Ma, Z.; Zuo, P.; Dai, L.; Wang, L.; Jia, H.; et al. Realization of high-luminous-efficiency InGaN light-emitting diodes in the “green gap” range. *Sci. Rep.* **2015**, *5*, 10883. [[CrossRef](#)]
21. Bi, Z.; Lenrick, F.; Colvin, J.; Gustafsson, A.; Hultin, O.; Nowzari, A.; Lu, T.; Wallenberg, R.; Timm, R.; Mikkelsen, A.; et al. InGaN Platelets: Synthesis and Applications toward Green and Red Light-Emitting Diodes. *Nano Lett.* **2019**, *19*, 2832–2839. [[CrossRef](#)]
22. Iida, D.; Zhuang, Z.; Kirilenko, P.; Velazquez-Rizo, M.; Najmi, M.A.; Ohkawa, K. 633-nm InGaN-based red LEDs grown on thick underlying GaN layers with reduced in-plane residual stress. *Appl. Phys. Lett.* **2020**, *116*, 162101. [[CrossRef](#)]
23. Kneissl, M.; Seong, T.-Y.; Han, J.; Amano, H. The emergence and prospects of deep-ultraviolet light-emitting diode technologies. *Nat. Photonics* **2019**, *13*, 233–244. [[CrossRef](#)]
24. Lee, D.-g.; Choi, Y.; Jung, S.; Kim, Y.; Park, S.; Choi, P.; Yoon, S. High-efficiency InGaN red light-emitting diodes with external quantum efficiency of 10.5% using extended quantum well structure with AlGaIn interlayers. *Appl. Phys. Lett.* **2024**, *124*, 121109. [[CrossRef](#)]
25. Liu, C.; Ooi, Y.K.; Islam, S.M.; Xing, H.G.; Jena, D.; Zhang, J. 234 nm and 246 nm AlN-Delta-GaN quantum well deep ultraviolet light-emitting diodes. *Appl. Phys. Lett.* **2018**, *112*, 011101. [[CrossRef](#)]
26. Xing, K.; Hu, J.; Pan, Z.; Xia, Z.; Jin, Z.; Wang, L.; Jiang, X.; Wang, H.; Zeng, H.; Wang, X. Demonstration of 651 nm InGaN-based red light-emitting diode with an external quantum efficiency over 6% by InGaN/AlN strain release interlayer. *Opt. Express* **2024**, *32*, 11377. [[CrossRef](#)]
27. Zhang, S.; Zhang, J.; Gao, J.; Wang, X.; Zheng, C.; Zhang, M.; Wu, X.; Xu, L.; Ding, J.; Quan, Z.; et al. Efficient emission of InGaN-based light-emitting diodes: Toward orange and red. *Photonics Res.* **2020**, *8*, 1671. [[CrossRef](#)]
28. Narukawa, Y.; Ichikawa, M.; Sanga, D.; Sano, M.; Mukai, T. White light emitting diodes with super-high luminous efficacy. *J. Phys. D-Appl. Phys.* **2010**, *43*, 354002. [[CrossRef](#)]
29. Lv, Q.; Liu, J.; Mo, C.; Zhang, J.; Wu, X.; Wu, Q.; Jiang, F. Realization of Highly Efficient InGaN Green LEDs with Sandwich-like Multiple Quantum Well Structure: Role of Enhanced Interwell Carrier Transport. *ACS Photonics* **2018**, *6*, 130–138. [[CrossRef](#)]
30. Chen, Z.; Yan, S.; Danesh, C. MicroLED technologies and applications: Characteristics, fabrication, progress, and challenges. *J. Phys. D-Appl. Phys.* **2021**, *54*, 123001. [[CrossRef](#)]
31. Jiang, F.; Zhang, J.; Xu, L.; Ding, J.; Wang, G.; Wu, X.; Wang, X.; Mo, C.; Quan, Z.; Guo, X.; et al. Efficient InGaN-based yellow-light-emitting diodes. *Photonics Res.* **2019**, *7*, 144. [[CrossRef](#)]
32. Zhou, X.; Lu, T.; Zhu, Y.; Zhao, G.; Dong, H.; Jia, Z.; Yang, Y.; Chen, Y.; Xu, B. Surface Morphology Evolution Mechanisms of InGaN/GaN Multiple Quantum Wells with Mixture N₂/H₂-Grown GaN Barrier. *Nanoscale Res. Lett.* **2017**, *12*, 354. [[CrossRef](#)] [[PubMed](#)]
33. Wu, Q.-f.; Cao, S.; Mo, C.-l.; Zhang, J.-l.; Wang, X.-l.; Quan, Z.-j.; Zheng, C.-d.; Wu, X.-m.; Pan, S.; Wang, G.-X.; et al. Effects of Hydrogen Treatment in Barrier on the Electroluminescence of Green InGaN/GaN Single-Quantum-Well Light-Emitting Diodes with V-Shaped Pits Grown on Si Substrates. *Chin. Phys. Lett.* **2018**, *35*, 098501. [[CrossRef](#)]
34. Li, Y.; Yan, S.; Hu, X.; Song, Y.; Deng, Z.; Du, C.; Wang, W.; Ma, Z.; Wang, L.; Jia, H.; et al. Effect of H₂ treatment in barrier on interface, optical and electrical properties of InGaN light emitting diodes. *Superlattices Microstruct.* **2020**, *145*, 106606. [[CrossRef](#)]
35. Li, Y.; Yan, S.; Die, J.; Hu, X.; Song, Y.; Deng, Z.; Du, C.; Wang, W.; Ma, Z.; Wang, L.; et al. The influence of excessive H₂ during barrier growth on InGaN light-emitting diodes. *Mater. Res. Express* **2020**, *7*, 105907. [[CrossRef](#)]
36. Li, Y.; Liu, C.; Zhang, Y.; Jiang, Y.; Hu, X.; Song, Y.; Su, Z.; Jia, H.; Wang, W.; Chen, H. Realizing Single Chip White Light InGaN LED via Dual-Wavelength Multiple Quantum Wells. *Materials* **2022**, *15*, 3998. [[CrossRef](#)] [[PubMed](#)]
37. Behrman, K.; Kymissis, I. Micro light-emitting diodes. *Nat. Electron.* **2022**, *5*, 564–573. [[CrossRef](#)]
38. Sheen, M.; Ko, Y.; Kim, D.-u.; Kim, J.; Byun, J.-h.; Choi, Y.; Ha, J.; Yeon, K.Y.; Kim, D.; Jung, J.; et al. Highly efficient blue InGaN nanoscale light-emitting diodes. *Nature* **2022**, *608*, 56–61. [[CrossRef](#)]
39. Wang, L.; Ma, J.; Su, P.; Huang, J. High-Resolution Pixel LED Headlamps: Functional Requirement Analysis and Research Progress. *Appl. Sci.* **2021**, *11*, 3368. [[CrossRef](#)]
40. Xiong, J.; Hsiang, E.-L.; He, Z.; Zhan, T.; Wu, S.-T. Augmented reality and virtual reality displays: Emerging technologies and future perspectives. *Light-Sci. Appl.* **2021**, *10*, 216. [[CrossRef](#)]
41. Yu, L.; Wang, L.; Yang, P.; Hao, Z.; Yu, J.; Luo, Y.; Sun, C.; Xiong, B.; Han, Y.; Wang, J.; et al. Metal organic vapor phase epitaxy of high-indium-composition InGaIn quantum dots towards red micro-LEDs. *Opt. Mater. Express* **2022**, *12*, 3225. [[CrossRef](#)]
42. Zhuang, Z.; Iida, D.; Ohkawa, K. Ultrasmall and ultradense InGaIn-based RGB monochromatic micro-light-emitting diode arrays by pixilation of conductive p-GaN. *Photonics Res.* **2021**, *9*, 2429. [[CrossRef](#)]
43. Chen, Z.; Sheng, B.; Liu, F.; Liu, S.; Li, D.; Yuan, Z.; Wang, T.; Rong, X.; Huang, J.; Qiu, J.; et al. High-Efficiency InGaIn Red Mini-LEDs on Sapphire Toward Full-Color Nitride Displays: Effect of Strain Modulation. *Adv. Funct. Mater.* **2023**, *33*, 2300042. [[CrossRef](#)]
44. Li, P.; Li, H.; Yao, Y.; Lim, N.; Wong, M.; Iza, M.; Gordon, M.J.; Speck, J.S.; Nakamura, S.; DenBaars, S.P. Significant Quantum Efficiency Enhancement of InGaIn Red Micro-Light-Emitting Diodes with a Peak External Quantum Efficiency of up to 6%. *ACS Photonics* **2023**, *10*, 1899–1905. [[CrossRef](#)]
45. Sun, Y.; Zhou, K.; Sun, Q.; Liu, J.; Feng, M.; Li, Z.; Zhou, Y.; Zhang, L.; Li, D.; Zhang, S.; et al. Room-temperature continuous-wave electrically injected InGaIn-based laser directly grown on Si. *Nat. Photonics* **2016**, *10*, 595–599. [[CrossRef](#)]
46. Yang, T.; Chen, Y.-H.; Wang, Y.-C.; Ou, W.; Ying, L.-Y.; Mei, Y.; Tian, A.-Q.; Liu, J.-P.; Guo, H.-C.; Zhang, B.-P. Green Vertical-Cavity Surface-Emitting Lasers Based on InGaIn Quantum Dots and Short Cavity. *Nano-Micro Lett.* **2023**, *15*, 223. [[CrossRef](#)] [[PubMed](#)]

47. Raun, A.; Hu, E. Ultralow Thresh. Blue Quantum Dot Lasers: What's True Recipe Success? *Nanophotonics* **2020**, *10*, 23–29. [[CrossRef](#)]
48. Wang, D.; Zhu, T.; Oliver, R.A.; Hu, E.L. Ultra-low-threshold InGaN/GaN quantum dot micro-ring lasers. *Opt. Lett.* **2018**, *43*, 799–802. [[CrossRef](#)] [[PubMed](#)]
49. Feng, M.; Zhao, H.; Zhou, R.; Tang, Y.; Liu, J.; Sun, X.; Sun, Q.; Yang, H. Continuous-Wave Current Injected InGaN/GaN Microdisk Laser on Si(100). *ACS Photonics* **2022**, *10*, 2208–2215. [[CrossRef](#)]
50. Zi, H.; Fu, W.Y.; Cheung, Y.F.; Damilano, B.; Frayssinet, E.; Alloing, B.; Duboz, J.-Y.; Boucaud, P.; Semond, F.; Choi, H.W. Comparison of lasing characteristics of GaN microdisks with different structures. *J. Phys. D-Appl. Phys.* **2022**, *55*, 355107. [[CrossRef](#)]
51. Tajiri, T.; Sosumi, S.; Shimoyoshi, K.; Uchida, K. Fabrication and optical characterization of GaN micro-disk cavities undercut by laser-assisted photo-electrochemical etching. *Jpn. J. Appl. Phys.* **2023**, *62*, SC1069. [[CrossRef](#)]
52. Zhao, L.; Chen, J.; Liu, C.; Lin, S.; Ge, X.; Li, X.; Hu, T.; Ding, S.; Wang, K. Low-threshold InGaN-based whispering gallery mode laser with lateral nanoporous distributed Bragg reflector. *Opt. Laser Technol.* **2023**, *164*, 109480. [[CrossRef](#)]
53. Chen, K.J.; Häberlen, O.; Lidow, A.; Tsai, C.L.; Ueda, T.; Uemoto, Y.; Wu, Y. GaN-on-Si Power Technology: Devices and Applications. *IEEE Trans. Electron. Devices* **2017**, *64*, 779–795. [[CrossRef](#)]
54. Cai, Y.; Zhou, Y.; Chen, K.J.; Lau, K.M. High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment. *IEEE Electron. Device Lett.* **2005**, *26*, 435–437. [[CrossRef](#)]
55. Cui, J.; Wei, J.; Wang, M.; Wu, Y.; Yang, J.; Li, T.; Yu, J.; Yang, H.; Yang, X.; Wang, J.; et al. 6500-V E-mode Active-Passivation p-GaN Gate HEMT with Ultralow Dynamic RON. In Proceedings of the 2023 International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 9–13 December 2023; pp. 1–4. [[CrossRef](#)]
56. Zheng, Z.; Song, W.; Zhang, L.; Yang, S.; Wei, J.; Chen, K.J. High I_{ON} and I_{ON}/I_{OFF} Ratio Enhancement-Mode Buried p-Channel GaN MOSFETs on p-GaN Gate Power HEMT Platform. *IEEE Electron. Device Lett.* **2020**, *41*, 26–29. [[CrossRef](#)]
57. Zheng, Z.; Zhang, L.; Song, W.; Feng, S.; Xu, H.; Sun, J.; Yang, S.; Chen, T.; Wei, J.; Chen, K.J. Gallium nitride-based complementary integrated circuits. *Nat. Electron.* **2021**, *4*, 595–603. [[CrossRef](#)]
58. Chen, J.; Liu, Z.; Wang, H.; He, Y.; Zhu, X.; Ning, J.; Zhang, J.; Hao, Y. A GaN Complementary FET Inverter With Excellent Noise Margins Monolithically Integrated With Power Gate-Injection HEMTs. *IEEE Trans. Electron. Devices* **2022**, *69*, 51–56. [[CrossRef](#)]
59. Xie, Q.; Yuan, M.; Niroula, J.; Sikder, B.; Greer, J.A.; Rajput, N.S.; Chowdhury, N.; Palacios, T. Highly Scaled GaN Complementary Technology on a Silicon Substrate. *IEEE Trans. Electron. Devices* **2023**, *70*, 2121–2128. [[CrossRef](#)]
60. Keller, S.; Li, H.; Laurent, M.; Hu, Y.; Pfaff, N.; Lu, J.; Brown, D.F.; Fichtenbaum, N.A.; Speck, J.S.; DenBaars, S.P.; et al. Recent progress in metal-organic chemical vapor deposition of (000) N-polar group-III nitrides. *Semicond. Sci. Technol.* **2014**, *29*, 113001. [[CrossRef](#)]
61. Li, Y.; Jiang, Y.; Jia, H.; Wang, W.; Yang, R.; Chen, H. Superior Optoelectronic Performance of N-Polar GaN LED to Ga-Polar Counterpart in the “Green Gap” Range. *IEEE Access* **2022**, *10*, 95565–95570. [[CrossRef](#)]
62. Li, C.; Zhang, K.; Qiaoyu, Z.; Yin, X.; Ge, X.; Wang, J.; Wang, Q.; He, C.; Zhao, W.; Chen, Z. High quality N-polar GaN films grown with varied V/III ratios by metal-organic vapor phase epitaxy. *RSC Adv.* **2020**, *10*, 43187–43192. [[CrossRef](#)] [[PubMed](#)]
63. Li, Y.; Hu, X.; Song, Y.; Su, Z.; Wang, W.; Jia, H.; Wang, W.; Jiang, Y.; Chen, H. Epitaxy N-polar GaN on vicinal Sapphire substrate by MOCVD. *Vacuum* **2021**, *189*, 110173. [[CrossRef](#)]
64. Li, Y.; Hu, X.; Song, Y.; Su, Z.; Wang, W.; Jia, H.; Wang, W.; Jiang, Y.; Chen, H. The role of AlN thickness in MOCVD growth of N-polar GaN. *J. Alloys Compd.* **2021**, *884*, 161134. [[CrossRef](#)]
65. Li, Y.; Hu, X.; Song, Y.; Su, Z.; Jia, H.; Wang, W.; Jiang, Y.; Chen, H. The influence of temperature of nitridation and AlN buffer layer on N-polar GaN. *Mater. Sci. Semicond. Process.* **2022**, *141*, 106423. [[CrossRef](#)]
66. Yamada, S.; Shirai, M.; Kobayashi, H.; Arai, M.; Kachi, T.; Suda, J. Realization of low specific-contact-resistance on N-polar GaN surfaces using heavily-Ge-doped n-type GaN films deposited by low-temperature reactive sputtering technique. *Appl. Phys. Express* **2024**, *17*, 036501. [[CrossRef](#)]
67. Romanczyk, B.; Wienecke, S.; Guidry, M.; Li, H.; Ahmadi, E.; Zheng, X.; Keller, S.; Mishra, U.K. Demonstration of Constant 8 W/mm Power Density at 10, 30, and 94 GHz in State-of-the-Art Millimeter-Wave N-Polar GaN MISHEMTs. *IEEE Trans. Electron. Devices* **2018**, *65*, 45–50. [[CrossRef](#)]
68. Koksaldi, O.S.; Haller, J.; Li, H.; Romanczyk, B.; Guidry, M.; Wienecke, S.; Keller, S.; Mishra, U.K. N-Polar GaN HEMTs Exhibiting Record Breakdown Voltage Over 2000 V and Low Dynamic On-Resistance. *IEEE Electron Device Lett.* **2018**, *39*, 1014–1017. [[CrossRef](#)]
69. Hamwey, R.; Hatui, N.; Akso, E.; Wu, F.; Clymore, C.; Keller, S.; Speck, J.S.; Mishra, U.K. First Demonstration of an N-Polar InAlGaN/GaN HEMT. *IEEE Electron Device Lett.* **2024**, *45*, 328–331. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.