Next Nanotechnology 5 (2024) 100056

Contents lists available at ScienceDirect

Next Nanotechnology

journal homepage: www.sciencedirect.com/journal/next-nanotechnology

Research article

Nanomaterial integration in micro LED technology: Enhancing efficiency and applications

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ARTICLE INFO

Keywords:
Micro LED technology
Nanomaterial integration
Gallium nitride (GaN)
High-performance displays
III-Nitride nanostructures

ABSTRACT

The micro-light emitting diode (μLED) technology is poised to revolutionise display applications through the introduction of nanomaterials and Group III-nitride nanostructures. This review charts state-of-the-art in this important area of micro-LEDs by highlighting their key roles, progress and concerns. The review encompasses details from various types of nanomaterials to the complexity of gallium nitride (GaN) and III nitride nanostructures. The necessity to integrate nanomaterials with III-nitride structures to create effective displays that could disrupt industries was emphasised in this review. Commercialisation challenges and the economic enhancement of micro-LED integration into display applications using monolithic integrated devices have also been discussed. Furthermore, different approaches in micro-LED development are discussed from top-down and bottom-up approaches. The last part of the review focuses on nanomaterials employed in the production of micro-LED displays. It also highlights the combination of III-V LEDs with silicon LCDs and perovskite-based micro-LED displays. There is evidence that efficiency and performance have improved significantly since the inception of the use of nanomaterials in manufacturing these.

1. Introduction

In advancing the technology of micro-LED, particularly for augmented and virtual reality (AR and VR), increasing requests for high-resolution displays have played a key role[1,2]. The backdrop of LED can be traced back to 1927 through Oleg Losev's pioneering work on the first LED, which was originally limited to infrared, red and yellow colors [3]. Shuji Nakamura's demonstration of an efficient blue LED in 1994 was a turning point in history. Materials such as Gallium Nitride (GaN) or Indium Gallium Nitride (InGaN) were used in these LEDs to emit blue light with high efficiency [3]. The relationship between Gallium Nitride (GaN) and Indium Gallium Nitride (InGaN) lies in their role as key materials in Light-Emitting Diodes (LEDs), specifically for efficient blue light emission. GaN is commonly used for blue and green LEDs, while InGaN, as a ternary semiconductor alloy, is utilised to fine-tune the emission wavelength and produce various colors, including blue [4]. On the other hand, Nuclear Magnetic Resonance (NMR) spectroscopy is a technique employed to study molecular properties. It plays a vital role in analysing compounds related to LED materials or investigating the chemical properties of substances used in LED production [5,6]. Semiconducting materials combined with phosphors converts blue light into red and green, resulting in a wide spectrum of white light in the field of white LED lighting. These LEDs were noted for their energy efficiency, converting a significant proportion of electric energy into visible blue light that reduces heat waste and ensures a long lifetime. Blue LEDs are crucial in technologies such as Blu-ray Disc players and high-density optical storage systems [4]. Micro-LEDs consist of microscopic LED chip arrays that improve energy efficiency, brightness, response times,

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https://doi.org/10.1016/j.nxnano.2024.100056
Received 20 November 2023; Received in revised form 27 January 2024; Accepted 22 February 2024
Available online 12 March 2024

and lifespan [7]. The semiconductor chip is made of p-type and n-type layers, causing the existence of a p-n junction that leads to light emission. The presence of holes in the p-type layer and electrons in the n-type constitute their positive and negative charge carriers, respectively. The establishment of the p-n junction entails a depletion region as a result of charge carrier migration. When applying forward bias, it implies attaching a positive voltage at the p-side and a negative voltage at the n-side, thus reducing the junction's potential barrier. Consequently, this bias allows for the movement of charge carriers (electrons and holes) across the junction that leads to light emission. The energy bandgap of the semiconductor material determines the color of emitted lights [8,9]. Phosphor-coated white LEDs are essential for display technology, which uses blue light to create dynamic colours. Display systems based on red, green, and blue light-emitting diodes (RGB-LEDs) use additive colour mixing to produce vivid images. It has three separate LED chips namely, red, green and blue. By manipulating the intensity of these three colours, many additional colours can be obtained. The applications of RGB LEDs are prevalent in changing or customisable lighting situations [10,11]. Pixel pitch, display resolution determination and Nits are some of the key factors that influence the efficiency of LED displays. Nits in LED displays, are a unit of measurement for luminance, representing the amount of visible light emitted by a source per unit of area. Essentially, Nits indicate the brightness of an LED display, and the term is derived from the Latin word "nitere," meaning to shine or glitter. To expand the lifespan of LED displays, it is necessary to comply with Electromagnetic Compatibility (EMC) standards [12–14]. At present, micro-LED displays have outperformed OLEDs or Organic Light Emitting Diodes in terms of brightness and lifetime. Apple's new approach involves replacing Thin-Film Transistor (TFT) backplanes with micro-Integrated Circuit (IC) drivers for better self-reliance [15,16]. The recent improvements in micro-LED technology, as a case in point, suggest that micro-LEDs could be a practical replacement for Organic Light-Emitting Diodes (OLEDs) and Liquid Crystal Displays (LCDs) in some cases [17]. OLEDs are made from carbon-based organic compounds and consist of multiple organic layers sandwiched between a transparent anode and a reflective or transparent cathode. The ability to emit light directly upwards makes OLEDs unique [18]. Jin et al. [7] improved quantum efficiency in microdisk LEDs, whereas Tian et al. [19] invention of flexible micro-LED arrays enabled fast data transmission. Fig. 1 illustrates improved pixel density for micro-LEDs from 2007 to 2019, portraying the advancements amid the challenges faced by full-color large-scale displays, reaching approximately 2000 pixels per inch (PPI) [20]. Singh et al. [21] highlighted the rapid modulation of micro-LEDs for visible light communication at high speed, thus demonstrating their appropriateness in quick data transfers. Also, Choi et al., [22] integrated GaN micro-LED arrays with sapphire microlenses and emphasises the critical role of optical engineering. Tull et al., [23] integrated LEDs with nanomaterials containing Group III-V elements from the periodic table and silicon thin film transistors to enhance the efficiency. The combination of Group III and V elements leads to compound semiconductors that are important for electronics and optoelectronics. For continuous research and development, refining fabrication techniques and overcoming technical challenges are necessary to bridge the gap between current achievements and the continuous challenge of achieving high PPI displays. μLED technology is transforming the landscape of Augmented Reality (AR) experiences [24,25]. Saphlux's micro-LED microdisplay employed Nano-Patterned Gallium Nitride (NP GaN), as well as quantum dots, with a superlative light conversion efficiency in 2020 of over 90% [26]. μLED technology made significant progress in 2022 and 2023. PlayNitride developed a prototype with a density of up to 4536 pixels per inch (PPI) [27]. Jade Bird Display introduced a native color monolithic micro-LED microdisplay using Indium Gallium Nitride (InGaN) and Aluminum Indium Gallium Phosphide (AlInGaP) epitaxy. MIT's vertically stacked μLEDs achieved an impressive pixel density of 5100 PPI via a two-dimensional material-based layer transfer process [28]. In its advances in the area of full-color micro-LEDs, PlayNitride has creatively integrated red, green, and blue (RGB) micro-LEDs onto one chip. At the pixel level, advanced technologies are employed to make each pixel emit red, green, and blue lights independently for full-color capabilities[27].

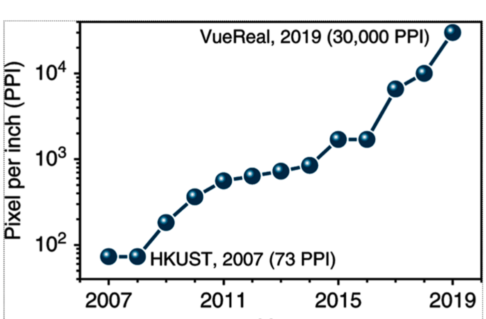

Fig. 1. Pixels per inch (PPI) roadmap of μ-LED displays from 2007 to 2019 [20].

Remarkably, the landscape of display technology has undergone a great revolution due to commendable changes in micro-LED technology, seen in its brightness, energy consumption and excellent picture quality. The struggle to produce high Pixel Per Inch (PPI) displays, especially in Augmented Reality is ever-recurring. Micro-LED's developmental trajectory is detailed in Table 1, focusing on its evolution and current state. Inarguably, micro-LEDs are revolutionary components in display technology. Nevertheless, manufacturing a micro-LED is complicated,

Table 1
Chronological progress and milestones in micro-LED Array development from 2000 to 2023.

Year	Micro-LED Description	Key Findings
2000	Theoretical groundwork for micro-LED by Jiang et al. [7]	Laid theoretical and experimental foundations for micro-LED technology
2001	10 × 10 blue micro-LED array with a 12 μm chip size by Jiang et al. [29]	Fabricated a small-scale blue micro-LED array
2004	64 × 64 UV micro-LED array with a 20 μm chip size by Dawson et al. [22]	Successfully developed a large-scale UV micro-LED array
2007	16 × 16 blue micro-LED array with a 72 μm chip size by Dawson et al. [30]	Demonstrated a small-scale blue micro-LED array using a flip-chip structure
2008	64 × 64 blue, green, and UV micro-LED array with a 20 μm chip size by Poher et al. [31]	Created a multi-color micro-LED array with a small chip size
2011	160 × 120 green micro-LED array with a 12 μm chip size by Lin et al. [32]	Established a high-resolution green micro-LED array using indium bump flip-chip bonding
2013	UV and RGB micro-LED arrays with a 50 μm chip size (360 PPI) by Liu et al. [33]	Achieved UV and RGB micro-LED arrays with moderate resolution
2014	Blue micro-LED arrays with a 15 μm chip size (1700 PPI) by Liu et al. [34]	Developed high-resolution blue micro-LED arrays
2015	128 × 128 RGB micro-LED array with a 35 μm chip size on a UV-based array by Kuo et al. [35]	Fabricated an RGB micro-LED array using UV and quantum dots (QDs) spraying technology
2017	Improved QD spraying accuracy and reduced pixel crosstalk using a photoresist mold by Kuo et al. [36]	Enhanced accuracy in QD application to micro-LED arrays
2020	Green micro-LED array with a 3.6 μm chip size on a sapphire substrate by Wang et al. [37]	Developed a green micro-LED array without involving the mesa etching process
2023	Vertical full-color micro-LED array with 5100 PPI and a 4 μm chip size by researchers from MIT, US, and South Korean Universities [28]	Achieved the highest PPI with the smallest chip size using 2D material layer transfer technology

making the cost of production higher than anticipated, and there are difficult challenges involved as well. Samsung has come up with new-generation TV sets based on this trend. Apple, for instance, reveals this potential through disruptive innovations, and it is believed that the introduction of micro-LED will pave the way for a new era of displays. These strategies often bring to the market new technologies, business models, or products that disrupt existing practices and can result in significant market shifts. This review provides a detailed analysis of the use of nanomaterials in micro-LED technology with an emphasis on increased efficiency and diverse applications. It is important to examine specific nanomaterials and their utilisation in micro-LED more closely to gain a full understanding of their roles. The importance of such materials goes beyond just improved efficiency; it also covers enabling various functions in the micro-LED sphere. The use of nanomaterials allows for improvements in performance and functionality. Therefore, the paper highlights the versatility of nanomaterials such as quantum dots and nanostructured phosphors in different kinds of micro-LED applications where further studies are essential for better insights.

2. Nanomaterials and III-nitride nanostructures

III-Nitride nanostructures consisting of nitrides of gallium (GaN), aluminum (AlN) and indium (InN), are key building blocks for the intricate world of semiconductor physics and technology [38]. Proximity to the band edge makes them ideal for use in micro-LEDs, increasing their brightness and energy efficiency. The emission wavelength of micro-LEDs can be precisely controlled by the compositional flexibility provided by III-Nitride alloys [38]. Classic considerations usually recommend Aluminum Indium Gallium Nitride (AlInGaN) and Aluminum Indium Gallium Phosphide (AlInGaP) alloys for this intricate tuning process [39–41]. To attain high-speed operation in micro-LEDs, particularly needed in high image resolution displays and fast-refresh-rate screens, this III-Nitride material has superior electron mobility [40,41]. The toughness and steady performance of micro-LED displays become possible due to the sturdy quality of III-Nitride materials, particularly gallium nitride (GaN) [19]. The use of nanoscale engineering further improves flexibility in design [42]. GaN and its alloys, such as AlGaN (Aluminum Gallium Nitride) and InGaN (Indium Gallium Nitride), with an emphasis on GaN that directs and governs the micro-LED fabrication process, significantly enhance light emission efficiency [43]. Careful control of the emission wavelength via deliberate modulation of III-Nitride alloy composition is essential for this purpose, in which Gallium Nitride (GaN) takes a lead role [44,45]. III-Nitride nanostructures' inherent features make them key components in intricate micro-LED designs. Direct bandgap, tunable wavelength, high electron mobility, durability and miniaturisation capabilities set new limits for achievable advancements with this technology [37]. The basis of comprehending cross-substrate applications and offering solutions lies in understanding GaN nanowire growth mechanisms. The first few steps of GaN nanowire growth were carried out using Plasma-assisted Molecular Beam Epitaxy (MBE) to show that it was possible to grow on various surfaces [46]. With successful selective area growth (SAG) processing for GaN nanowires on different substrates, attention has shifted to versatility and wide applicability. By using a titanium nitride

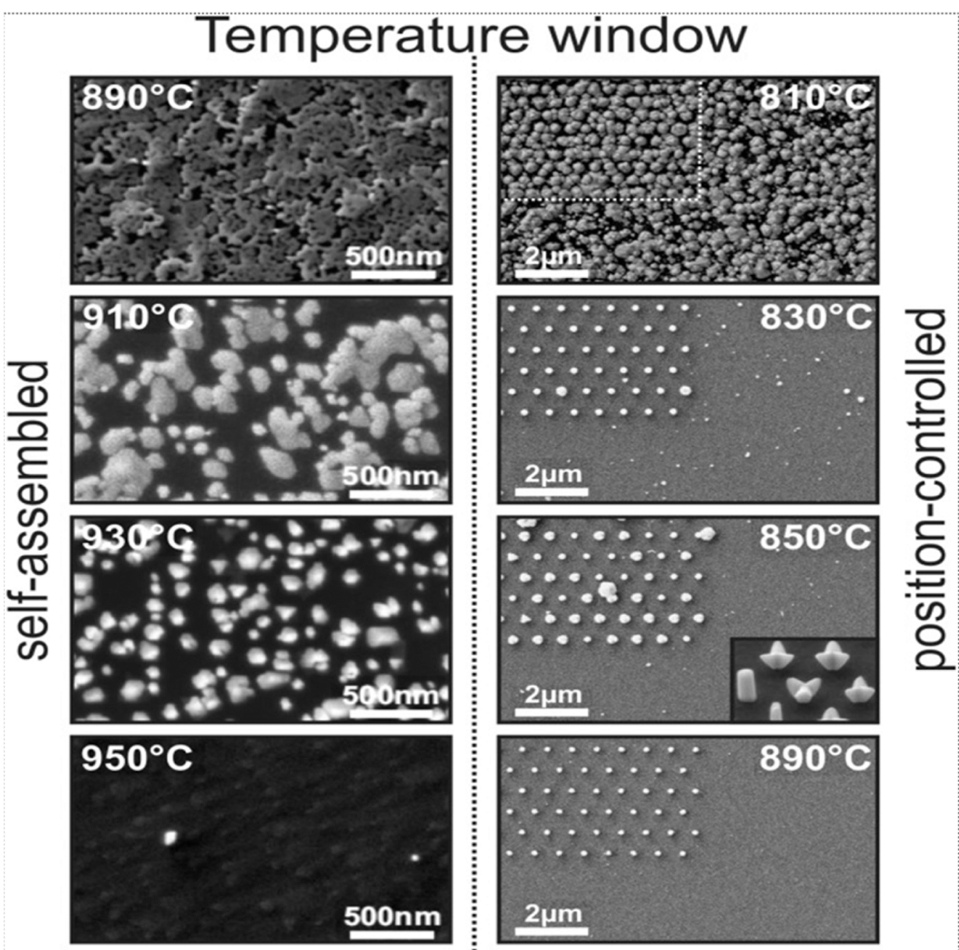

Fig. 2. SEM images, illustrating (left) self-assembled and (right) selective area growth (SAG) of GaN nanowires (NWs) on diamond at various substrate temperatures [48].

nanomask, this not only demonstrates that the method can be applied to various materials but also expands the scope for future advances in nanowire-based devices [47]. A careful study into temperature regions needed for growing GaN nanowires over diamond substrates is given. Self-assembled growth requires a higher absolute substrate temperature within a narrow range of approximately 20 K, whereas SAG occurs in a larger window of about 60 K. SEM images in Fig. 2 compellingly depict a seamless transition from a layer-like morphology to well-defined nanowires at elevated temperatures. These serve as persuasive evidence of the intricate processes taking place. These insights into nucleation site distribution and nanowire morphology offer relevant knowledge for growth condition optimisation. SEM images depict (left) self-assembled and (right) SAG of GaN nanowires (NWs) on diamond at different substrate temperatures. With approximately 0.5% and 1.0% for self-assembled and SAG, respectively, effective III/V flux ratios have been used in both methods [48]. This is because the ratio of group III to group V elements in the precursor chemicals (III/V flux ratio) was estimated to be about 0.5% for self-assembled growth and 1.0% for SAG growth. This parameter determines the composition and properties of semiconductor materials during their development, making the III/V flux ratio vital in their growth. In this case, it gives an idea of how each element is used during the growing processes [49,50].

Fig. 3 provides information on the study of GaN nanowire growth on diamond substrates using various microscopy techniques. Fig. 3(a) displays a cross-sectional High-Angle Annular Dark-Field Scanning Transmission Electron Microscopy (HAADF STEM) and color-coded Energy-Dispersive Electron Spectroscopy (EELS) mapping, revealing the structure of a self-assembled GaN nanowire on a diamond substrate rather than presenting atomic species. Aberration-corrected Annular Bright-Field Scanning Transmission Electron Microscopy (ABF STEM), rendered by false colors, is shown in Fig. 3(b), indicating wurtzite Ga-N bilayers and revealing the N-polarity of the nanowire. In Fig. 3(c), a High-Resolution Transmission Electron Microscopy (HRTEM) image was taken to demonstrate GaN interacting with diamond, facilitating a more profound understanding at the level of structure. Finally, power spectra are provided in Fig. 3(d), displaying that an epitaxial relationship between GaN nanowire and diamond substrate exists [51].

Exploration of the growth of InGaN nanowires challenge existing assumptions and marks a radical break with previous understanding. To achieve quasi-stoichiometric growth by aligning the metal flux with nitrogen flux, the goal reverses the course for all growth parameters. The motivation for this pursuit is to have total mastery over features of InGaN nanowires, which are crucial elements in optoelectronic devices like LEDs and photodetectors [52]. Gallium Nitride (GaN) is another semiconductor with a wide bandgap and is used in many electronic and optoelectronic devices [53]. The InGaN nanowire based on GaN nanowires under different growth conditions is depicted in Fig. 4, contributing to a broader understanding of the InGaN nanowire growth kinetics. The study of InGaN nanowires emitting at around 600 nm unveils the effect of growth conditions, as reflected by various optical

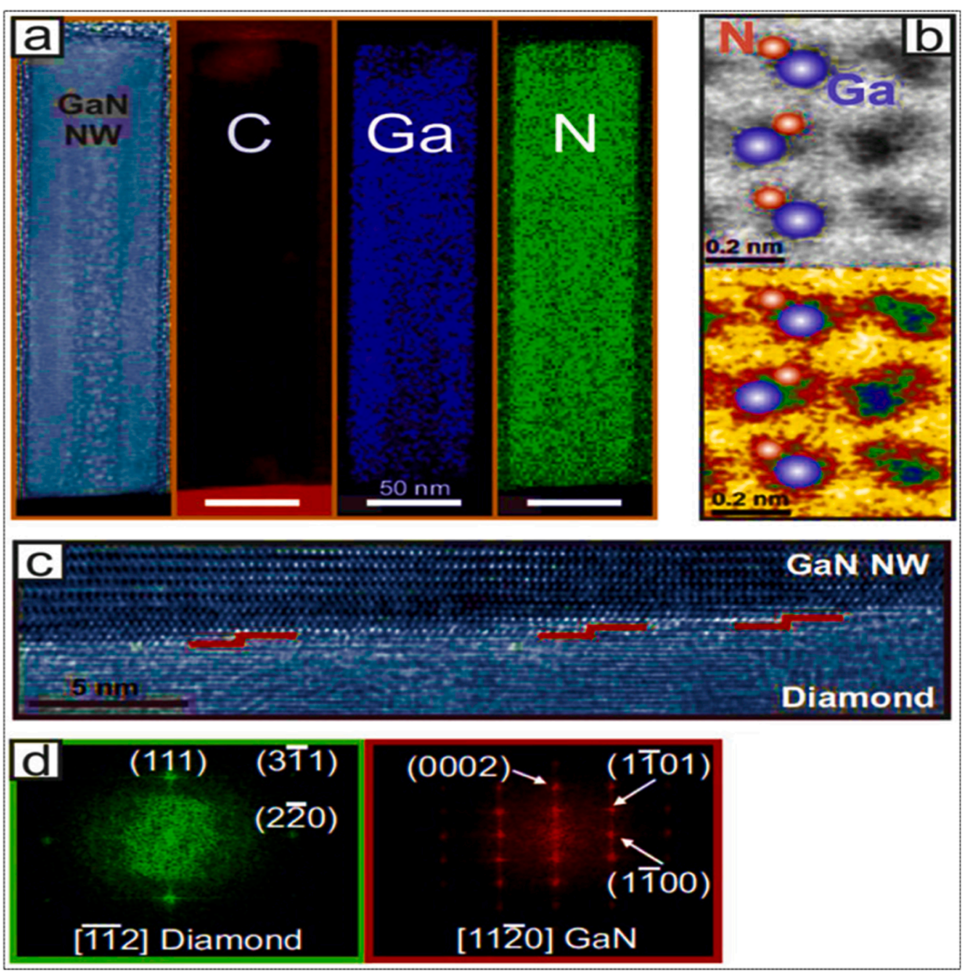

Fig. 3. (a) Cross-sectional HAADF STEM and color-coded EELS mapping reveal different atomic species in a self-assembled GaN nanowire (NW) on a diamond substrate, (b) An Annular Bright-Field Scanning Transmission Electron Microscopy (ABF STEM) image, represented in false colors(e.g., used to enhance contrast and highlight specific details that may not be easily distinguishable in grayscale), exhibits wurtzite Gallium nitride (Ga-N) bilayers, indicating N-polarity, (c) High-resolution transmission electron microscopy (HRTEM) image at GaN/diamond interface, (d) Epitaxial relationship by power spectra [51].

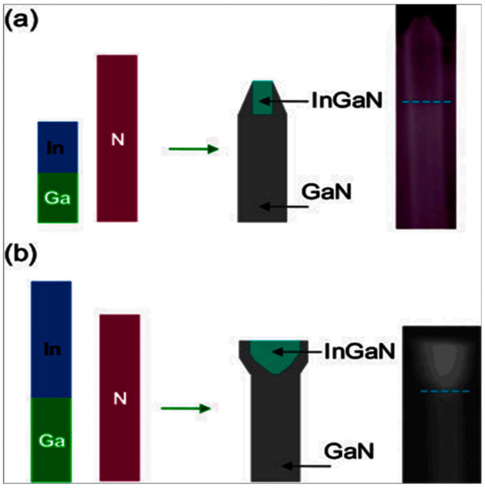

Fig. 4. Schematics of Indium Gallium Nitride (InGaN) Nanowire (NW) growth on Gallium Nitride (GaN) NW base. (a) Growth in nitrogen-rich conditions illustrating the formation of a self-controlled InGaN/GaN core/shell structure, (b) Growth of the InGaN section in metal-rich conditions, resulting in the widening of the InGaN section and the formation of a core/shell structure[53].

behaviors and structural changes [53]. The integration of III-Nitride nanostructures into micro-LEDs is the leading cause of technological advancement in the field of advanced electronics and optoelectronics. This effort, in conjunction with knowledge about growth mechanisms as well as substrate-dependent behaviors, establishes a robust foundation for nanowire-based devices and cutting-edge display systems [52]. In the exploration of Gallium Nitride (GaN) nanowire growth, gaining insight concerning growth dynamics and interface characteristics is crucial for optimising conditions. The growth process schematically depicted in Fig. 4(a) demonstrates self-controlled InGaN/GaN core/shell structure formation under nitrogen-rich conditions. Consequently, through growth in metal-rich conditions, the section of InGaN widens, expanding the InGaN section to form a core/shell structure as illustrated in Fig. 4(b). However, it emphasises that, contrary to common belief, closely matching metal flux with nitrogen flux is crucial for quasi-stoichiometric growth. Fig. 4 demonstrates that different InGaN structures can be obtained by varying conditions during the process. Therefore, it provides an improved understanding necessary to optimise growth conditions to obtain desired results in InGaN nanowire formation, where these outcomes are needed. This understanding is essential for optimising growth conditions and achieving desired outcomes in InGaN nanowire formation [53].

To understand the complex interaction between the growth conditions and optical properties in InGaN nanowires, macro-photoluminescence spectroscopy serves as a great aid. Fig. 5 illustrates spectra from macro-photoluminescence spectroscopy, indicating a wide

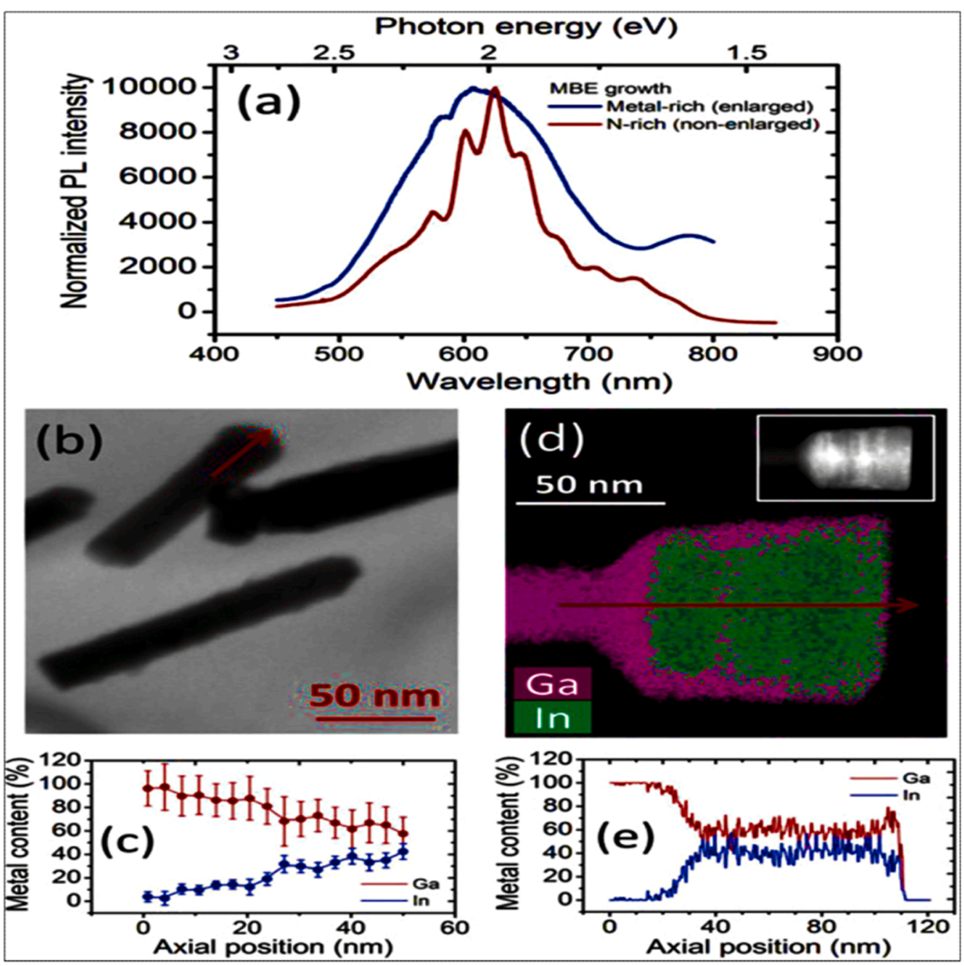

Fig. 5. (a) Macro-photoluminescence spectroscopy spectra of InGaN Nanowires (NWs) emitting in the 600 nm range in nitrogen-rich (non-enlarged) and metal-rich (enlarged) conditions, respectively. (b), (d-inset) Scanning electron microscopy images of InGaN NWs grown in nitrogen-rich and metal-rich conditions, respectively. (d) In and Ga Energy-Dispersive X-ray (EDX) mapping of the InGaN section grown in metal-rich conditions. (c), (e) In and Ga concentration profiles along the growth axis of InGaN NWs grown in nitrogen-rich and metal-rich conditions, respectively [53].

photoluminescence peak width of nitrogen-rich and metal-rich grown InGaN nanowires. These spectra show variations in composition due to different growth conditions. For instance, when it comes to nanowires grown in metal-rich conditions, their chemical composition is thoroughly examined using advanced techniques that include Energy-Dispersive X-ray (EDX) mapping and concentration profiles. Gallium (Ga) and Indium (In) are clearly depicted in Fig. 5(a), and their influence on the photoluminescence peak width is evident in macro-photoluminescence spectroscopy spectra of InGaN nanowires with emission at around 600 nm in nitrogen-rich and metal-rich conditions. In nitrogen-rich and metal-rich conditions, scanning electron microscopy images of InGaN nanowires are represented by Fig. 5(b) and its inset, respectively. An energy-dispersive X-ray (EDX) map of the InGaN section grown under metal-rich conditions is given in Fig. 5(d), which presents a different view. The distribution of In and Ga revealed through energy-dispersive X-ray (EDX) analysis can be seen from Fig. 5(d). Fig. 5 (c) and (e) give concentration profiles of Ga and Indium (In) along the growth axis, thereby comparing nitrogen-rich and metal-rich growth conditions [53]. In materials science, a notable success was accomplished when researchers initiated an epitaxial relationship with substrates to enable the control of material growth along specific directions [54]. In the nanomaterials field, there have been advances in synthesis techniques, peculiar properties (mechanical, optical), and its future uses like drug delivery or sensing [55–57]. In addition, such strides are aimed at making materials that suit different applications [58–61]. The key to this breakthrough is systematic exploration of growth mechanisms, which can be highlighted by looking at the type of mechanisms involved in detail [62]. For example, nucleation and crystallisation processes were thoroughly examined by the scientists, thus indicating their detailed approach to understanding forces behind materials growth [63,64].

Nickel-Gold (Ni-Au) catalyst particles play a crucial role in orienting nanowires, as illustrated in Fig. 6. It is noteworthy that various sapphire planes are alternative substrates for the growth of nanowires. Fig. 6(a) and (b) demonstrate that manipulation of Ni-Au catalyst composition can effectively control growth directionality, illustrating the importance of catalysts in this process. This is in line with observations by Tsivion et al. [62], demonstrating controlled nanowire growth on millimeter-long horizontal nanowires across different sapphire planes, as depicted in Fig. 6(c). Growth conditions influence nanowire orientation, as seen in Fig. 6(d). It is obvious from this figure that the preference for the growth direction is almost always perpendicular to the substrate. The latter is promising for improving device efficiency and target features by creating elongated structures of nanowires [62,65]. Looking at crystallographic orientations, the vertical alignment of Gallium Nitride (GaN) nanowires on the (111) oriented silicon brings about simplicity for easy incorporation into devices. The directionality of GaN nanowires' growth on r-plane Al_2O_3 indicates that a catalyst can alter orientation. It also points out the adaptiveness and scalability of NW growth techniques. In the wider context of nanowire growth and semiconductor processes, the choice of the silicon crystal plane like silicon (111) greatly affects the alignment, morphology, and properties of

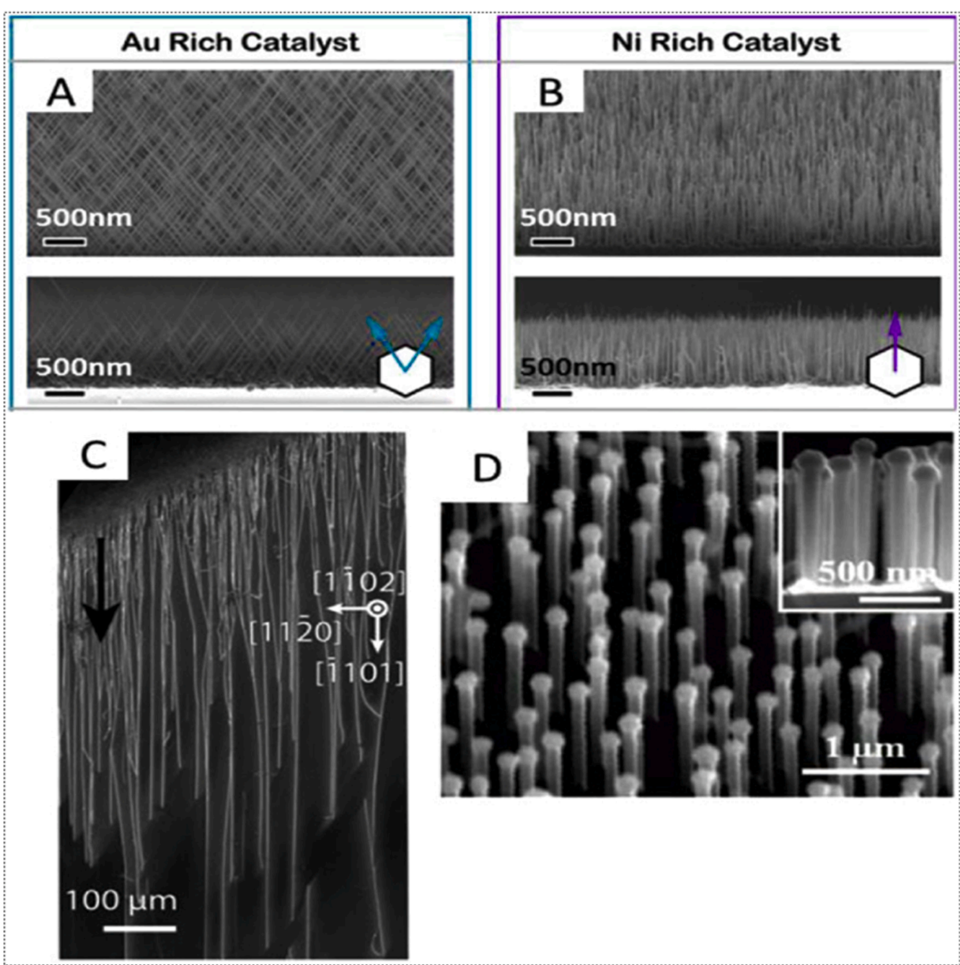

Fig. 6. Illustration of controlled growth directions in GaN nanowires on r-plane Al_2O_3. Panels (A) and (B) the successful manipulation of growth direction by adjusting the composition of the Ni-Au catalyst particle, Panel (C) millimeter-long horizontal nanowires on different planes of sapphire Panel (D) highlights vertically aligned GaN nanowires grown on Si (111), an orientation often preferred for simplified integration into devices[66].

resulting structures. In certain growth conditions on (111) orientation, there is a well-known preference for vertical alignment, making this particular orientation suitable for some applications in semiconductor device integration. Continuous-flow Metalorganic Chemical Vapor Deposition (MOCVD) has been shown to be useful in generating high-quality Ga-polar nanowires. This detailed study highlights catalysts, growth conditions, and crystallographic orientations intricately interacting to control nanowire structures with designed properties and applications [66,67]. The nature of Ga-polar nanostructures is significantly influenced by the choice of non-nitridated sapphire as a substrate. Ga-polar nanowires have a gallium atom-enriched surface. These are tiny structures, generally in the diameter range of a few nanometers. The MOCVD technology has demonstrated great flexibility in designing GaN/AlGaN nanowire structures. These involve hybrid combinations of GaN and AlGaN, the materials that may or may not contain quantum dots. Such structures have certain optical properties at low temperatures [66].

The determination of temperature-dependent optical characteristics for Ga-polar nanowires reveals the intricacies of their stability and reliability for optoelectronic applications, as demonstrated in Fig. 7. Among the particularities of Gallium Nitride (GaN), there is its direct bandgap, which appears to be an important factor for the advancement of micro-LED technology. The optimisation of both optical and electronic properties within GaN nanostructures may be achieved by the use of quantum dots, size-dependent properties, and nanostructured phosphors [66]. The enhancement of micro-LED performance at its core is characterised by merging precise engineering and synthesis techniques, fusing principles from materials science and semiconductor physics [68, 69]. At 5 K, the micro-photoluminescence results observed in Ga-polar nanowires grown by continuous-flow Metalorganic Chemical Vapor Deposition (MOCVD) demonstrate exceptional optical quality. The optical signal clarity and precision are evident, with a peak Full Width at Half Maximum (FWHM) measuring about 0.95 meV. The inset in Fig. 7 (a) further dissects the observed donor-bound exciton and free exciton recombinations. Fig. 7(b) illustrates the microphotoluminescence at low temperature (4 K) of site-controlled GaN/AlGaN nanowires at different stages, both with and without Quantum Dots (QDs). This is an indirect indication that the chosen growth method can be flexible enough. At low temperatures (40 K), the microluminescence results demonstrate another way to see the versatility of the Metalorganic Chemical Vapor Deposition (MOCVD) technique in making GaN/AlGaN nanowires that may or may not have quantum dots in specific sites [66]. Therefore, this comprehensive examination of optical characteristics, depending on temperature, will not only extend our understanding of Ga-polar wires but also emphasise their applicability for micro-LED technology [70].

The reason for such progress in micro-LED performance is the integration of accurate engineering and synthesis techniques from materials science and semiconducting physics. Table 2 presents a comprehensive comparison outlining the effects of materials/substrates, growth conditions, as well as parameters on nanostructure and GaN nanowires (NWs). The influence of diamond and sapphire substrates has been studied using hydride vapor phase epitaxy (HVPE) and metal-organic chemical vapor deposition (MOCVD), shedding light on substrate effects. The table explains the vapor-liquid-solid (VLS) growth mechanism that underpins this through crystallography. Piezoelectric nanogenerators (PENGs) with GaN nanowires (NWs), InGaN/GaN LEDs, and PEC water splitting enhancement find an array of uses in piezoelectric nanogenerators, LEDs with InGaN/GaN, and enhanced Photoelectrochemical (PEC) water-splitting.

2.1. Micro-LED technology: categorisation and impact of nanomaterials

Micro-LED technology can transform display capabilities by improving pixel density, resolution, and color. In this context, it is worth noting that the effects of micro-LEDs are most conspicuous in AR/VR systems, including smartphones, wearable devices, televisions, as well as automotive displays. MicroLEDs demonstrate this characteristic by being scalable and can be used for different kinds of devices and display needs. They contribute in terms of precision and flexibility with respect to micro-LED-based devices (1–5 μm) and wearables (5–30 μm), while 5–50 μm-sized displays make phones more detailed and sharper. The larger a device like a television, the better the visual experience it offers (20–80 μm), whereas information is given in detail on an automotive display (50–100 μm). This characteristic is exhibited by digital displays (80–100 μm), highlighting that micro-LEDs can possibly change the entire appearance of the visual environment [2]. In the world of micro-LEDs, it is very important that combinations of different nanomaterials can ensure the proper control of light emission and equipment optimisation [89]. A colloidal suspension of quantum dots uses quantum mechanics principles to show unique optical and electronic properties. This is because they are tiny (<10 nm in size) semiconductor particles that are suspended in a liquid solution. Quantum dots are known for emitting specific colours depending on their size. This has enabled them to improve colour accuracy in display devices. The importance of this feature will be realised when it comes to colour accuracy, since precision in colour representation signifies everything in the displays field. This makes micro-LED displays more flexible when it comes to their colour ranges, which affects the quantum dots' ability to emit light over a wide range of colours as well. Therefore, in addition to being brighter, the latter enables them to generate even more colours that look more true-to-real-life applications [89,90]. Li et al. [90] demonstrates that micro-fluid technology improves display efficiency and expands the spectrum of colours. This is a significant improvement because a QD color conversion layer with 10-micrometer size pixels can enable

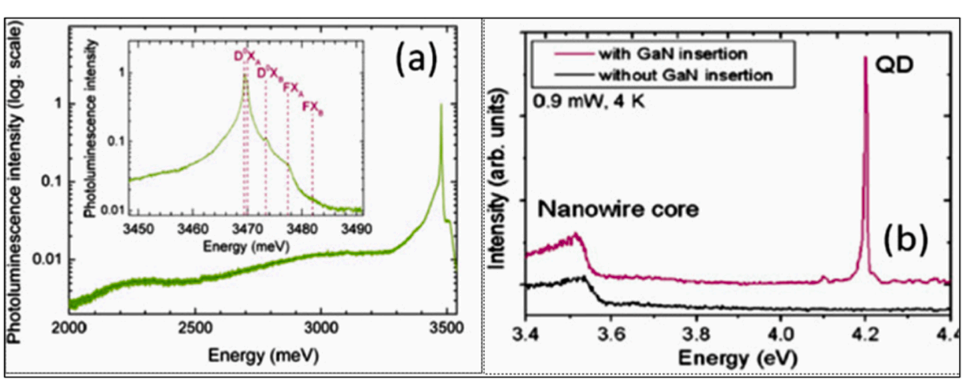

Fig. 7. The exceptional optical quality of the Ga-polar nanowires grown through the unconventional continuous-flow MOCVD approach, (a), A low-temperature (5 K) microphotoluminescence measurement of single GaN nanowires, obtained via self-assembled growth on c-sapphire, reveals a peak Full Width at Half Maximum (FWHM) of 0.95 meV. The inset identifies donor-bound exciton and free exciton recombinations, (b) displays a low-temperature (4 K) microphotoluminescence of single site-controlled GaN/AlGaN nanowires with quantum dots (QDs) or without [66].

Table 2
A Comprehensive Comparison of Materials/Substrates, Growth Conditions and Parameters, and their Effects on Growth Direction and Performance in Nanostructure and Gallium Nitride (GaN) Nanowires (NWs).

Materials/ Substrates	Growth Conditions and Parameters	Effects on Growth Direction and Performance	References
Semiconductor nanomaterials (nanotubes, nanowires, nanoparticles)	Vapor–liquid–solid (VLS) growth process with metal catalyst on substrate surface	Vertical or random out-of-plane orientations; Nonplanar NWs assembled into planar arrays using post-growth methods or surface-guided growth	[71,72]
Diamond Substrate	Used variable parameters	Substrate impact on GaN NW growth direction and performance	[73,74]
Sapphire Substrate	-Used variable parameters	Substrate impact on GaN NW growth direction and performance	[75]
Silicon Substrate	- Used variable parameters	Substrate impact on GaN NW growth direction and performance	[76]
SiC Substrate	Used variable parameters	Substrate impact on GaN NW growth direction and performance	[77,78]
n-type Si (111) substrate	MOCVD, Au NPs deposition, TMIn and TMGa injection, annealing for catalyst agglomeration, VLS to VS growth mode, GaN/InGaN MQW co-axial NWs	MOCVD, Au NPs, TMIn/TMGa, annealing, VLS to VS growth, Controlled growth direction	[79]
Beryllium oxide (BeO)	VLS approach, Au catalyst, Agglomeration, VLS to VS growth mode, GaN NWs on polycrystalline BeO, Vertical and slantingly aligned NWs, InGaN/ GaN MQW shells	VLS, Au catalyst, Agglomeration, VLS to VS growth, Vertical/slanting NWs	[80]
Graphene-coated monolayer Cu foil	VLS method with Au catalyst, Low-temperature growth, Single-crystal GaN NWs on metallic substrate, Controlled growth direction	VLS, Au catalyst, Low-temperature growth, Controlled direction	[81]
Amorphous glass substrate	Two-step VLS–VS growth method, Au/ In/Ga alloy catalyst, In situ post-growth nitridation, Triangular GaN core NWs, InGaN/GaN MQW shells, Homogeneous growth on glass	Two-step VLS–VS, Au/In/Ga catalyst, Nitridation, Triangular core NWs, Homogeneous growth	[82]
GaN NWs on Sapphire Substrate	MOCVD, VLS growth mode, Pristine and coaxial GaN NWs, SEM characterisation	MOCVD, VLS growth, Pristine/ coaxial NWs, Crystallographic orientation	[83]
GNWs with ZnS Overlayer	MOCVD, VLS and VS growth modes, ZnS shell thickness varied, PEC water-splitting performance, LSV curves, ABPE%, EIS spectra	MOCVD, VLS/VS growth, Varied ZnS thickness, PEC water-splitting performance	[84]
Ternary Sandwiched Nanostructure	MOCVD, VLS and VS growth modes, Au NPs sandwiched between GNW and ZnS	MOCVD, VLS/VS growth, Au NPs sandwiched, Improved PEC water-splitting performance	[84]
p-Si (1 1 1)	CVD with metallic Ga and NH3, GaN pre-layer as a self-catalyst	GaN NWs grown on GaN film, NH3 flow rates varied (0.4, 0.6, 0.8 L/min)	[85]
Gallium nitride (GaN) NWs	Synthesised using chemical vapor deposition (CVD) on R- and M-plane sapphire wafers with Ni catalyst	Improved electrical and optical performance; Surface-guided growth on different substrates with structural, optical, and electrical characterisation	[54,86]
Surface-guided growth on flat and faceted sapphire surfaces based on a growth model	Kinetics and Growth Mechanism of GaN NWs	Dimensionality of surface diffusion close to 2; Main diffusion pathway is adatom collection from substrate	[87]
NW Synthesis (GaN)	CVD method using Ga_2O_3 powder and ammonia gas on sapphire substrates; Ni catalyst deposition and annealing	Growth on flat R-plane and faceted M-plane sapphire substrates; Wurtzite crystal structure; Axial growth directions	[87]
Thinner GaN NWs on faceted Sapphire Surfaces	Envelope analysis of growth rates versus NW radius; Fitting data to growth model, Morphological differences on annealed M-plane and R-plane sapphire; Thinner NWs on faceted surface	Dimensionality of surface diffusion close to 2 for both substrates; Main diffusion pathway is adatom collection from substrate	[88]

Note- MOCVD (Metal-Organic Chemical Vapor Deposition), VLS (Vapor-Liquid-Solid), VS (Vapor-Solid), NPs (Nanoparticles), TMIn (Trimethyl Indium), TMGa (Trimethyl Gallium), MQW (Multiple Quantum Well), Au (Gold), BeO (Beryllium oxide), GNW (GaN Nanowire), ZnS (Zinc Sulfide), PEC(Photo-electrochemical), LSV (Linear Sweep Voltammetry).

high-resolution, full-color active-matrix micro-LED displays [91]. The significance of GaN micro-LEDs display in this area is due to their brightness as well as the ability to modulate each pixel individually [92]. Wu et al. [93] brought out submicron-scale LEDs, which could be used in emerging optoelectronics, especially virtual and augmented reality [15, 93]. In Fig. 8(a), this involves creating a core-shell structure and distinct morphology of InGaN-InGaN/AlGaN multiple-quantum-well nanowire array. Fig. 8(b) demonstrates that a similar peak wavelength of electroluminescence is maintained even with a one-order magnitude change in current injection, indicating the stability of the micro-LED at different operational conditions. Fig. 8(c) depicts the current-voltage characteristics that further illustrate practical application and performance [93]. Nano-grooves have been used to push the limits of micro-LED technology, highlighting the importance of nanostructures in this field [94]. Multidimensional advances in the domain of micro-LEDs can be seen through the convergence of mixed technologies and materials, indicating a future where screens will not only have sharper images and better color accuracy but also work with different applications on various devices.

Lozano et al.'s analysis of the ability of metal nanostructures to

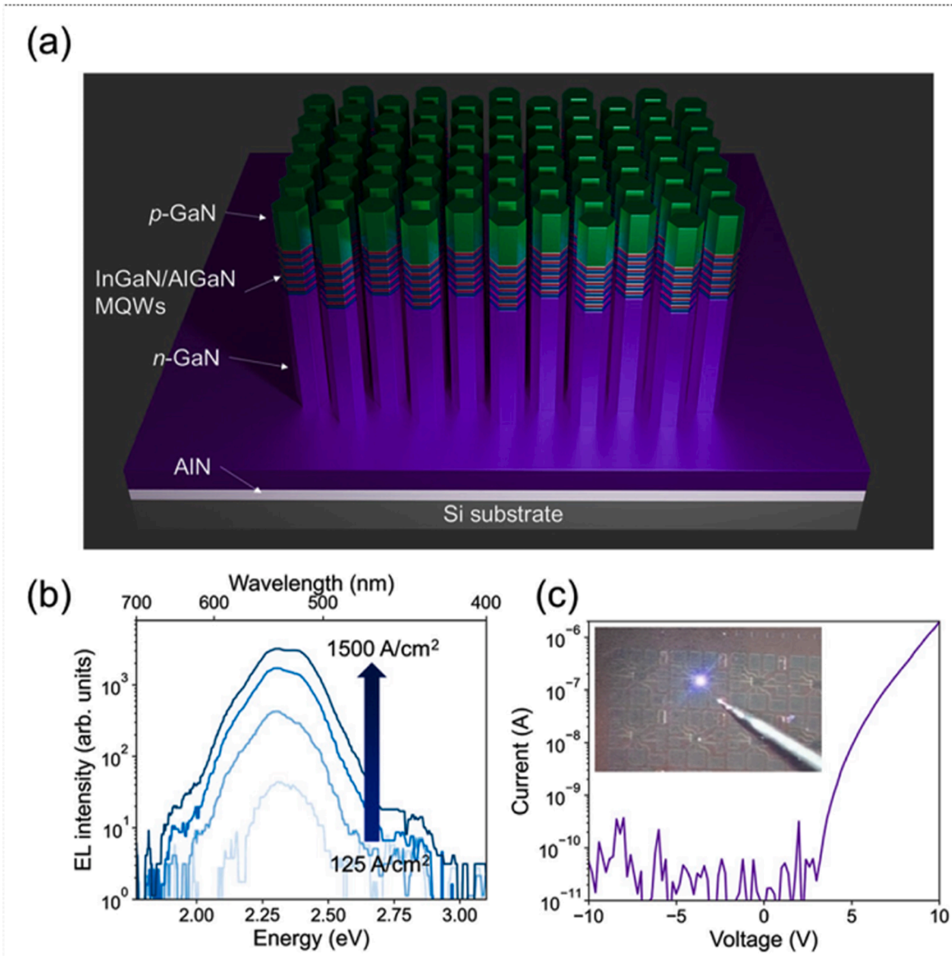

Fig. 8. (a) Schematic representation of the InGaN/AlGaN multiple-quantum-well nanowire array, illustrating the core-shell structure and unique morphology, (b) Graph depicting the consistent peak wavelength of the device's electroluminescence over a one-order-of-magnitude change in current injection, highlighting the stability of the μLED. (c) Current-voltage characteristics of the device exhibiting a strong green emission visible to the eyes and a good rectification ratio, emphasising the practical application and performance of the developed μLEDs[93].

control light emission dynamics is discussed in [95]. David et al.'s [96] introduction of coinage metal nanoclusters (MNCs) is a harbinger of innovative chromophores – a sign that they could have their place in cutting-edge lighting technologies. Sung et al. [97] demonstrates enhanced electroluminescence in GaN-based LEDs decorated with metal nanoparticles, marking the dawn of photon scattering and coupling as never before. Zhang et al.'s [99] investigation of tin dioxide nanoparticles provides insight into the Schottky barrier height adjustments at the Ag/p-GaN interface, which is an important contact for various electronic and optoelectronic applications where its properties affect device performance [98]. Zhu et al.'s [100] study on merging graphene films with single-walled carbon nanotube structure presents a unique material combination with improved optical and electrical characteristics and new possibilities for application in transparent conductive films [98,101]. The nanoparticles of metallic oxides demonstrate versatility, suggesting their importance in advancing display technology [102,103]. The contest for the highest colour performance and efficiency has given birth to several innovations in projection displays. There is a new theoretical model, the Quantum-Dot Color Wheel (QD-CW), which breaks the duty circle ratio and transcends color purity and gamut range constraints [104]. The duty cycle ratio is a measure of the time a particular color spends on display in a color wheel or similar device. For QD-CW, breaking the duty circle means changing or surpassing the classical time division among colors on the wheel [105,106]. To optimise the QD-CW device for better white balance, core-shell CdSe@ZnS Quantum Dots (QDs) were examined with respect to absorption and photoluminescence spectra [107,108]. The QD-CW device was fabricated using precise photolithography; consequently, it exhibits uniformity as well as smoothness in Quantum-Dot Color Conversion Layers (QDCCLs) [109,110]. Blue light leakage got eliminated, and light conversion efficiency increased as a consequence of incorporating up-to-date Distributed Bragg Reflector (DBR) technology into the structure [111,112]. When integrated into the display prototype, the QD-CW device expands the color gamut area compared to conventional color wheel systems through a complete cycle by ensuring synchronous blue, green, and red-light output [113]. Intriguing results were discovered during research on colour chromaticity change in liquid crystal display light guide panel that was caused by wavelength-dependent scattering. The incorporation of different nanomaterials into micro-LED displays provides an attractive way to improve performance, which includes alternative and innovative things related to the present demands of current exhibit technologies [114]. LEDs emit white light at the edge of the light guide, which is dispersed by the patterned dots at the bottom of the panel. Spatially, lights that are far away from LEDs appear to be reddish, while for those closer to LEDs, they have a bluish color. The color differences demonstrated, as quantified values, range between 0.01 and 0.06, emphasising the role played by light guide resin and thickness [115]. The Lambertian distribution of Mini-LEDs was employed to come up with a solution using a nonuniform quantum-dot color conversion film (QDCCF). Experimental results confirmed a considerable improvement in the uniformity of luminance (up to 89.91%). This was explained through ray tracing simulations. By enabling good white balance, high uniformity (92.15%), and a wide color gamut (109% NTSC), the application of the nonuniform QDCCF on the prototype gives hope for further progress in Mini-LED-based display technology[116]. The use of quantum dots, nanowires, metallic nanostructures, metal oxide nanoparticles, and graphene-based materials in micro-LED displays promises to improve their performance and visual vibrancy in the future.

3. Fabrication and integration of micro-LEDs for display applications

Manufacturing processes of Micro LED displays can greatly benefit from the use of advanced materials like polymer nanocomposites and graphene-based fibers [117,118]. Their performance is likely to be improved in numerous ways, including increased robustness, resilience against EMI and flexibility [119]. The integration will enable Micro LED technology to perform more reliably across various electronic devices [120]. Epitaxial growth is critical in defining the micro-LED crystalline structure, serving as the foundation of the technology [17]. The size and structure of each individual micro-LED are defined by lithography and etching, which are essential steps in ensuring accurate craftsmanship. Nevertheless, these difficulties become more pronounced with a decrease in lateral dimensions, leading to an "efficiency cliff [121,122]. Micro-LED production is a combined collaboration of two major methods of manufacturing: top-down and bottom-up techniques [123]. The conventional top-down processing using plasma etching mainly exacerbates the efficiency cliff through surface damage as well as crystal defects [124,125]. To improve surface stoichiometry and device characteristics, various strategies, including thermal annealing and N_2 plasma exposure, have been adopted to suppress plasma etch-induced damage [126]. Aiming at surface passivation [127,128], post-mesa etching surface treatments such as atomic layer deposition (ALD) and $(NH_4)_2S$ treatment have been used. This shows that post-mesa etching treatments of the semiconductor surface such as atomic layer deposition (ALD) and $(NH_4)_2S$ treatment are used to improve the properties of the semiconductor material for electronic device fabrication. Post-mesa is a term used in semiconductor fabrication to describe the processes and treatments given to a semiconductor device following mesa etching. It is a method where isolated regions or mesas are created on a silicon wafer. These mesas define the active areas of various devices, such as transistors or diodes Wet etching using KOH eliminates the leakage paths created during plasma etching, providing an idea about the depth of the crystal damaged by plasma [127–130]. Another important aspect is hydrogen plasma treatment, which deactivates Mg acceptors around the device mesa, raising peak EQE in green micro-LEDs [131]. Solutions to the lattice mismatch in InGaN alloys between GaN and InN include V-pits, n-GaN buffer layers, superlattices, pseudo-substrates, and Smart Cut™ technology [98,132–134]. It has been demonstrated that V-pits, thick n-GaN buffer layers, superlattices, and partial decomposition of InGaN underlayers are effective approaches to address the issue of efficient red emission. This may allow EQE to go beyond 1%, although this strategy is still faced with challenges involving defects [98, 132–134]. V-pits, V-shaped recesses that can form on the surface of GaN semiconductors during growth, are part of strategies to optimise the performance and reliability of GaN-based devices, such as high-electron-mobility transistors (HEMTs). Integrating multi-color micro-LEDs into high-resolution displays poses challenges, especially in achieving smaller LED chip sizes [135,136]. Both passive and active-matrix configurations present hurdles in pick-and-place mass transfer, defect identification, testing, and yield concerns [15]. Precision in the top-down technique involves the deliberate removal of larger materials, whereas the bottom-up method builds up structures layer by layer. The detailed discussion of top-down and bottom-up approaches can help understand more about the production of micro-LEDs. Developing ways to handle plasma etching challenges and InGaN alloy growth, coupled with advances in post-mesa etch treatments, can be considered important for improving micro-LED display technology moving forward.

3.1. Top-down approach in micro-LED patterns

In the realm of display technologies, the most important thing is to make micro-LEDs as accurately as possible using the top-down approach, where lithography, etching, and deposition are combined in an intricate manner. Lithography reveals the microLED pattern blueprint, which serves as a starting point for the complex manufacturing process [137]. The rest of the actions heavily rely on this accuracy-based step, as it determines microLEDs' properties and layout. Micro-LEDs are designed with precision via etching, a particular step in the top-down approach that engraves them meticulously by taking some material away from them, defining appropriate structures [138]. Micro-LEDs are thus sculpted with accuracy through this painstaking process to ensure optimal performance. Meticulous deposition is used to introduce depth into micro-LED structures and strategically place semiconductor and contact layers that would enhance their overall functionality [139]. This forms part of the structure that enhances the performance of these systems. In lithography and etching, as they engage in an iterative dance of refinement, micro-LED features are fine-tuned to closely match the desired specifications [140]. This means that through this process, every micro-LED is made to meet the exact design criteria. After that, there is a crescendo in the top-down approach, which is the deposition of metal contacts that help to form electrical connections essential for seamless communication within the micro-LED array [141]. This is the last stage of fabrication, and it guarantees that the micro-LED array will perform its functions. The precision required for advanced display technologies is encapsulated in the top-down approach used in micro-LED fabrication, which is likened to a symphony of technology [123]. This pushes the boundaries of visual display capabilities, and each step contributes to the synergy of processing and technology. It starts with lithography and ends with metal contacts deposition [137].

3.2. Bottom-up approach in micro-LEDs with precision

The landscape of micro-LED fabrication has evolved, with both top-down and bottom-up approaches demonstrating technological advancements. SAG, a technique allowing direct growth of micro-LEDs on the substrate, is the cornerstone of the bottom-up approach [142]. For instance, this process fine-tunes indium concentrations in InGaN platelets to control colors on displays. It seems SAG could be the way to go for precise fabrication of micro-LEDs. Self-assembly and quantum dot integration, which are underpinned by SAG, are among bottom-up techniques that promise displays with resolutions as high as possible, with unbeatable precision. However, they have their fair share of challenges. It is extremely challenging to consistently retain quality assembly at large scales. Bottom-up approaches must be handled delicately to avoid having this approach become too expensive in terms of production costs. The choice between mass transfer for larger displays and monolithic integration for smaller ones becomes critical in the light of the ongoing development of Mini-LED and micro-LED displays [143]. It is important to note that this decision determines the scalability, cost-effectiveness, and overall success of micro-LED displays in the market. A paradigm shift in visual experiences is heralded by this, as diverse applications are integrated into the future, where micro-LED displays seamlessly integrate with each other – made possible by the complex interplay between top-down and bottom-up approaches [144]. The comprehensive exploration of fabrication techniques is facilitated through the coexistence of these approaches, thus leading to the development of micro-LED technology. A bottom-up approach can provide higher precision and resolution in micro-LED displays, for example, through techniques such as SAG.

3.3. Mass transfer and monolithic integration

Epitaxial growth, which is a key element, shapes crystalline structures, leading to the development of micro-LEDs [145]. Processes such as lithography and etching represent the measurements of each micro-LED's size and structure, guaranteeing accuracy in performance. Nevertheless, these difficulties become more pronounced with a decrease in lateral dimensions, leading to an efficiency cliff [124,125]. Micro-LED production benefits from both top-down and bottom-up approaches. Conventional top-down processes, such as plasma etching, worsen the efficiency decline by leading to damage of the surface and crystal defects [125,146,147]. Approaches like N_2 plasma exposure or thermal annealing may help mitigate plasma etch-induced damage [126]. Some examples of such post-mesa etching surface treatments include atomic layered deposition (ALD) and chemical treatment, which are used to passivate surface states [127,128]. Identification of defects and mass transfer challenges has made the mass transfer of Micro LEDs, both in active-matrix and passive-matrix, more complex, thereby requiring testing as well as addressing yield concerns [15]. In this case, the interplay of top-down with bottom-up approaches is a pointer to a future where micro-LED displays will fuse into different applications, leading to a breakaway from traditional visual encounters [145]. This is seen through the coexistence of both methods in making various fabrication techniques that help in advancing micro-LED technology. Micro-LED technology advances mass transfer and monolithic integration. However, there are major challenges that have been solved by introducing innovative solutions. For example, PDMS stamp transfer of X-Celeprint and laser transfer method of SONY. Fig. 9 presents the two models of mass transfer and monolithic integration illustrated schematically [148].

3.3.1. Micro-LEDs through monolithic integration

Paradigm shift in micro-LED technology can be seen through monolithic integration, whereby epitaxial wafers undergo a metamorphosis, altering their form into intricately arranged chip arrays. These arrays perfectly couple with color conversion materials that result in unmatched precision and vibrancy of display effects [145]. The array of uses for monolithic integration is highlighted to include the integration of InGaN/GaN LED (Light Emitting Diode) chips with vertical MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) or AlGaN/GaN HFETs (High Electron Mobility Transistors). This requires combining optoelectronic devices and those that are electronic on a single substrate of semiconductor, such as in micro-LED technology, which aims at developing small-sized and multifunctional semiconducting devices for power-efficient and optoelectronic systems [94, 149,150]. As a result, there is an expansion of opportunities through a fusion offering better functions and properties in the integrated systems. A groundbreaking development in this field is Zhang et al.'s[151] pioneering fusion of monolithic integrated device (MID) technology with Micro LEDs [152], which creates new frontiers in display technology. InGaN/GaN LED chips are the most commonly used LED materials due to their high light emission efficiency and comprise Indium Gallium Nitride (InGaN) as its active layer and the semiconductor element made up of Gallium Nitride (GaN) [70,151]. When combined with Moulded Interconnect Device (MID) technology—where electronic circuits are directly integrated into 3D moulded plastic components—it opens up possibilities for advanced and compact LED applications. This is because MID technology allows for intricate and space-efficient designs, thereby enabling the seamless integration of InGaN/GaN LED chips into different products and devices. Consequently, this integration pushes the industry to never-before-reached heights, which promise revolutionary advances in micro-LED displays' abilities [152]. The transition of micro-LEDs via monolithic integration implies a drastic change in display technology by bringing together several technologies, such as InGaN/GaN LED chips and MID technology, to expand the realm of possibilities.

3.3.2. Moulded Interconnect Device (MID) technology

Moulded Interconnect Devices (MIDs), the leading edge of modern electronics, combine seamlessly with micro-LED integration, initiating a pivotal shift in display technology [153,154]. Landmarks in electronic manufacturing include the use of Leneke et al.'s [155] revolutionary 3D-MID[156] multilayer process that is redefining the limits of micro-LED can be achieved [154]. Moser et al.'s [144] exploration of Moulded Interconnect Devices (MIDs) in automotive applications highlights the potential for integrating all functionalities onto a single chip. It indicates a path wherein advanced display abilities in cars may be turned into reality, leading to not only better fuel consumption but also a much-improved user experience [157]. These types of integration change the whole system and are instrumental in improving the system integration that leads to efficiency gains, as well as more streamlined electronic architectures, thereby enabling the optimisation of electronic systems [156]. The seamless integration of MIDs with micro-LEDs is a merger that goes beyond the scope of electronics manufacturing and represents an important milestone in display technology. The display landscape is being transformed by mass transfer, monolithic integration, and MID technologies, which are being leveraged by micro-LED. This has been well demonstrated by the achievement of monolithic micro-LED displays on gallium-nitride-on-silicon substrates [154]. It further emphasises its versatility and adaptability to different display technologies, marking a significant step forward in the sector. In addition, manufacturing complexity, cost-effectiveness, and uniformity in large displays are not going to be easy ones to crack, being the key issues

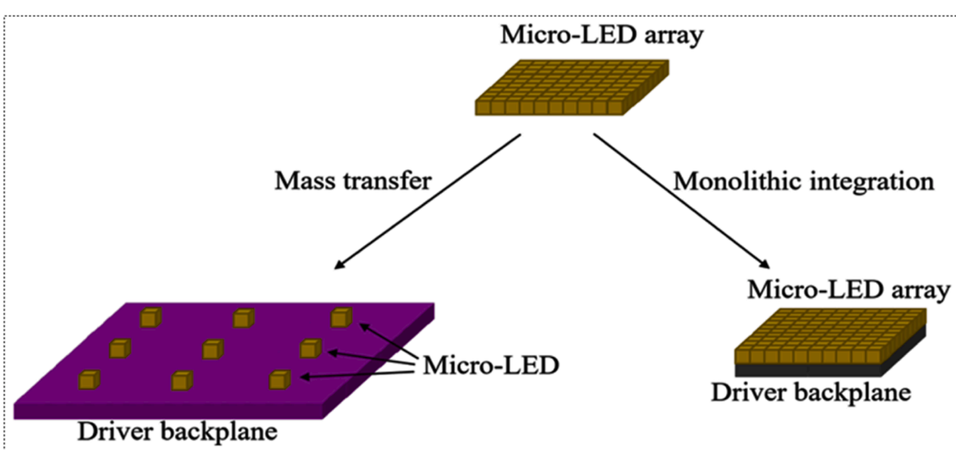

Fig. 9. Schematic diagram of two methods of mass transfer and monolithic integration[148].

of concern that demand close attention [154]. To address these challenges, there is a need for collective input from researchers, engineers, and industry players. Despite that, MIDs technology integration with micro-LEDs can improve display performances. The technological integration of both MIDs and micro-LEDs not only deals with the current problems but also provides new possibilities for better performance, efficiency, and feasibility in display applications [156–158]. However, critical challenges, including manufacturing complexity, cost-effectiveness, and uniformity in large displays, loom as pressing agendas that require meticulous attention [157].

4. Efficiency enhancement through nanomaterials and III-nitride nanostructures

Notably, recent research endeavors have improved the efficiency of micro-LEDs in the context of small-area blue InGaN micro-LEDs [46]. However, progress has been made to enhance efficiency in green and red micro-LEDs; yet, these developments underscore the importance of understanding efficiency cliffs in tiny devices [159]. LED efficiency evaluation is a widely used conventional approach that revolves around the external quantum efficiency (EQE), which has a direct relationship to light extraction efficiency (LEE) and internal quantum efficiency (IQE). Injection efficiency is another important parameter in this regard. For example, high LEE is a challenge for III-nitride LEDs since it arises from fundamental problems in extracting emitted light from semiconductor layers. This complication results from total internal reflection at GaN/sapphire interface or any other LED mechanism that causes light absorption [160]. The GaN/sapphire interface is the point where Gallium Nitride (GaN) merges with a sapphire substrate in LEDs, and this is the cause of complications in light extraction. Light trapping techniques are applied with a lot of thoughtfulness to optimise light extraction efficiency, lowering total internal reflection and thereby enhancing the likelihood that photons will slip out of the LED's structure, hence improving luminous output. Several mechanisms contribute to light absorption in an LED, including interaction with the active material (such as InGaN), absorption by different layers in the LED structure, and possible losses due to reflector or absorber materials inside the device [161]. The high refractive index of GaN (nGaN ~2.5) is particularly responsible for this absorption challenge, which leads to total internal reflection at the GaN/sapphire interface, light trapping and multiple mechanisms within the structure which contribute to light absorption in LED structures as described in Eq. (1) [162].

$$\mathbf{EQE} = \boldsymbol{\eta}_{\mathbf{inj}} \times \mathbf{light\ \ extraction\ \ efficiency} \times \mathbf{internal\ \ quantum\ \ efficiency} \quad (1)$$

Optoelectronics and high-power electronics have been significantly impacted by the development of AlN, GaN, and InN Group III nitride semiconductors. High-brightness visible LEDs are made possible by these semiconductors, which have revolutionised LED-based full-color displays to serve a wide range of purposes. In 1994, a major breakthrough was achieved in designing highly efficient blue LEDs, which proved their usefulness in various fields [163]. The ability to tune the bandgap makes ternary alloys like AlGaN, InGaN, and AlInN, and structures extremely versatile. These ternary alloys usually consist of Aluminum (Al), Gallium (Ga), Indium (In), and Nitrogen (N). Such ternary alloys with gallium nitride (GaN) as a representative are common in semiconductor materials, especially for the development of compound semiconductors. Literature often emphasises the importance of crystallographic polarity, especially for GaN deposited by plasma-assisted molecular beam epitaxy (PIMBE) on c-plane sapphire GaN/sapphire substrate, for hetero-epitaxial growth in III–V nitride semiconductors [45]. Difficulties in extracting emitted light from the semiconductor layers result in challenges in achieving high LEE in III-nitride LEDs. LEE is a key parameter for optimising the performance of III-nitride-based optoelectronic devices, like light-emitting diodes (LEDs), where it ensures that light is effectively extracted from the device. Therefore, it is important to improve LEE to achieve high brightness and energy efficiency of III-nitride LEDs [160]. Revolutionary micro-LED technology depends on the efficiency of III-nitride materials, like GaN, concerning its power conversion applications. In this sense, GaN-based power electronics can enhance energy conversion as well as increase the driving range in electric vehicles. Some of these methods include flip-chip and roughening the nitrogen face of n-GaN, which disrupts total internal reflection [164]. Fig. 10 represents that light extraction efficiency has changed over the years [165]. The micro-LED technology is revolutionised through the increase in efficiency, which is driven by III-nitride materials, particularly GaN. Moreover, power conversion in different sectors has been transformed by GaN-based devices for power electronics that improve energy conversion and extend electric vehicle range. Furthermore, III-nitride materials optimise the power conversion efficiency of solar power systems, thus enhancing the general performance of renewable energy sources. Consequently, the importance of III-nitride materials extends to various technologies, such as Lin et al.'s [166] work on UV detectors used to purify water and air[166].

The high-frequency and high-power electronics domain witnesses the importance of III-nitride materials, particularly InN, in driving developments in high-speed wireless communication systems, including but not limited to 5 G technology and beyond [167]. The race to increase the efficiency of micro-LEDs has led to research in new fabrication methods that are expected to overcome hindrances and fully exploit these revolutionary technologies. It is a method of improving efficiency through the use of PA-MBE and a Ti mask layer to pattern nanowire arrays on Ga-polar GaN-on-sapphire substrates. Here, GaN is a WBG semiconductor material that is grown on a sapphire substrate with a Ga-polar orientation, predominantly containing gallium atoms at the surface. PA-MBE has employed a plasma source from which it derives ionisation energy needed to undertake the deposition of GaN layers accurately, thus regulating growth conditions and properties of materials. The use of titanium (Ti) mask layer is one way of differentiating specific areas for epitaxial growth according to [168] thereby enabling development of complicated structures and better control overgrowth process of GaN on sapphire. This procedure is used in the production of GaN-based devices, such as high electron mobility transistors and LEDs, where the performance is optimised based on substrate orientation and controlled growth [169]. Results obtained by using high-resolution transmission electron microscopy (TEM) of the nanowires reveal an AlGaN shell, which can reduce surface recombination. The hole injection is further enhanced by an n++/p++ GaN tunnel junction contact layer, where there are heavily doped n-type (n++) and p-type (p++) regions during the process. As a result, green electroluminescence (EL) of micro-LEDs with high stability was realised, which had a maximum external quantum efficiency (EQE) of about 5.5% at 3.4 A/cm^2. The wavelength shift for semi-polar facets decreases as a function of

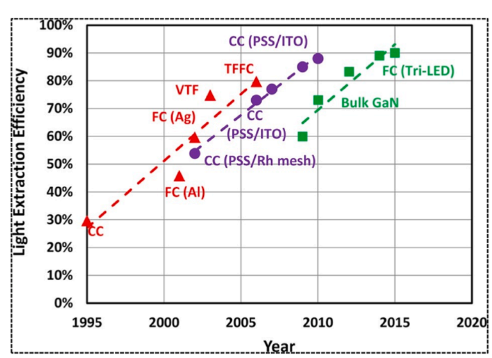

Fig. 10. Evolution of light extraction efficiency over time (FC: Flip-Chip, VTF: Vertical Thin Film, PSS: Patterned Sapphire Substrate, ITO: Indium Tin Oxide)[165].

injection current [170,171]. Enhancements in carrier injection and higher growth temperatures are found by the investigation of N-polar nanostructure-based LEDs. These nanowires have flat tops, and a layer of Aluminum Gallium Nitride (AlGaN) surrounds or encapsulates another material, protecting the active region from surface recombination. It implies an outer layer, and it's indicated by the composition of AlGaN, a ternary alloy of Aluminum (Al), Gallium (Ga), and Nitrogen (N) [172, 173]. As a result, N-polar micro-LEDs exhibit an EQE of −11% at 0.83 A/cm^2. The faceted nature of the InGaN active region can be seen in transmission electron microscopy (TEM) images, where there are facets on the active region composed of Indium Gallium Nitride (InGaN). Thus, the faceting promotes excitonic recombination, hence improving device efficiency [174,175]. Further examples include sub-micron LEDs emitting red light made using a thick InGaN segment, in addition to the successful N-polar green LEDs. The intensity of emission is enhanced via in-situ annealing, such that these devices exhibit higher efficiency than their counterparts from the top-down method [176,177]. The addition of an InGaN/GaN Short-Period Superlattice (SPSL) also further red shifts the emission, contributing to improved EQE and wavelength peak values. In the case of InGaN/GaN, this short-period super-lattice relates to a periodic arrangement consisting of alternating thin films comprising Indium Gallium Nitride and Gallium Nitride [178,179]. Achieving high-efficient long-wavelength light-emitting diodes (LEDs) is challenging because of low spectral purity. The effort to narrow down the emission spectrum is ongoing, as scientists experiment with photonic crystals in creating optical microcavities [179,180]. Inclusion of photonic crystals in micro-LEDs leads to Photonic Crystal (PhNC) devices that exhibit stable emission peaks and less efficiency droop. This development has the potential of solving challenges related to spectral impurity. Photonic crystals allow for light control by the use of periodic structures, hence enabling meticulous tuning of emitted characteristics within micro-LEDs. Improved spectral purity is inferred from the stability of emission peaks, while less efficiency droop shows more stable operation at high power levels [178,179]. The same technological advances are evident with nanocrystal surface-emitting lasers (NCSELs). For these devices, complex DBRs are not necessary, and they can also be used in selective area growth, demonstrating their flexibility even if they do not work well under high power. They would be applicable in communication, projectors, displays, and optical storage technology once packaged properly, and their thermal needs are managed [181–183]. For better performance of micro-LEDs, nanostructures, especially III-nitride, should be incorporated [184,185]. The integration of nanomaterials, such as III-nitride nanostructures, on the other hand, enhances the performance of micro-LEDs [186]. This integration supports further development of Micro LED technology that will enable flexible and transparent micro-LED displays, which would represent a significant leap from current display technologies [185]. Slimane et al.'s [187] study is a full inquiry into this transformative period of time, stressing III-Nitride micro and nano structures for solid state lighting. The need to explore advanced materials, innovative fabrication techniques, and improved substrate designs still exists, despite historical methods, including coating blue LEDs with yellow phosphor or using RGB LED combinations to achieve white light in LEDs [187]. Wierer et al.[188] examines the operational challenges unique to micro-LEDs that require further research to improve their performance and reliability [189]. Fig. 11 illustrates that III-nitride materials have transformed conventional wisdom, leading to the development of brighter and energy-efficient white light sources [190]. Advancements in III-nitride technology have brought forth highly efficient blue LEDs, which have revolutionised lighting, leading to more sustainable and visually improved lighting solutions. This integration of III-nitride materials exemplifies their influential role in shaping the course of modern technology with broad implications for various applications in electronics, optoelectronics, etc [191–193].

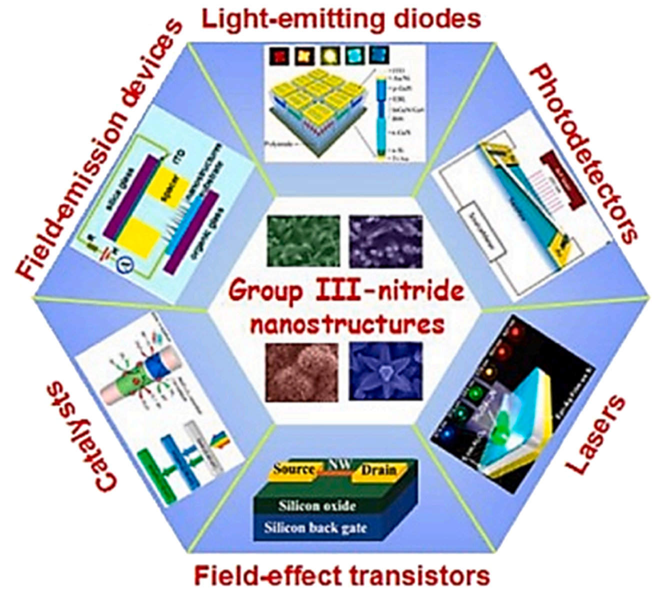

Fig. 11. Revolutionising Illumination: Blue LED Technology and III-Nitride Semiconductors [190].

5. Nanomaterial integration and III-nitride nanostructures in micro LED display applications

The progress in the development of GaN-based LEDs (Light Emitting Diodes) using gallium nitride (GaN) has been remarkable, contributing to the exceptional performance capabilities of GaN-based LEDs. GaN, a wide-bandgap semiconductor material, has played a pivotal role in advancing LED technology, particularly in the domain of solid-state lighting [194]. For efficient light emission, there has been a significant boost in GaN material improvement, which has led to its highly desirable properties. There has been great improvement since the introduction of advanced InGaN heterojunction and quantum-well LEDs that have significantly improved brightness and efficiency [195]. These devices are key components in many applications due to their high brightness and efficiency, which result from continuous optimisation of materials as well as design principles employed. Fig. 12 illustrates the basic elements and operating principles of a double heterostructure LED [165]. The schematic includes key elements such as the substrate, epitaxial layers, and the process of electron and hole recombination in the active region, ultimately resulting in the emission of photons.

The motivation behind achieving with III-nitride LEDs was a way to find out if it was possible to come up with a true-blue LED, which was later realised in the 1990 s. The breakthroughs of the 1980 s that included Metal-Organic Chemical Vapor Deposition (MOCVD)-assisted growth of high-quality GaN-on-sapphire opened the avenue for uniform and high-crystallinity GaN films fabrication. This solved compatibility issues among direct bandgap semiconductors [196]. Fig. 13 illustrates important milestones in the history of development of the first GaN-based light-emitting p–n junction diode [39].

Though several different types of quantum dots are used, indium gallium nitride (InGaN)-based quantum dots integrated into III-nitride nanostructures, especially in InGaN-based nanomaterials, have aided a lot in the development of Micro LED technology [197]. This exploits size-dependent quantum effects to improve optical properties and broaden color gamut while enhancing color accuracy. To achieve efficient red emission on InGaN/GaN-based LED chips, some novel approaches such as SU-8 bonding and aerosol jet printing with QDs ink have been developed [47,198]. Fig. 14 provides an extensive description of micro-LED technology that includes full-colour display emissions, precision of aerosol jet printing, optical configurations for projection systems, and intricate nano-pillar LED structures. Fig. 14(a) shows the

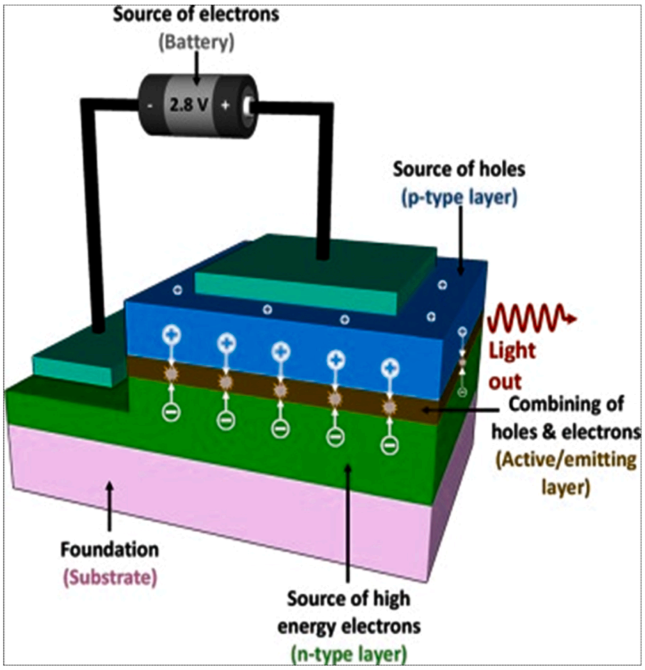

Fig. 12. Simplified illustration of a double heterostructure LED, providing a visual representation of its fundamental components and operation [165].

emission of full-colour sub-pixels under a microscope [199]. Fig. 14(b) illustrates the aerosol jet printing technology [199,200]. Fig. 14(c) demonstrates an optical setup for a projection system [199,201]. Lastly, Fig. 14(d) shows the methods and electron microscope view of embedded nano-pillar LED creation [199,202].

Micro-LEDs take precedence in terms of picture quality and a reduced risk of problems such as screen burning compared to OLEDs (Organic Light-Emitting Diodes). Nonetheless, the manufacturing process of larger micro-LED screens may be complex and expensive. Due to their flexibility acknowledged in literature and designs, OLEDs are mostly preferred for applications requiring design flexibility [203]. Fig. 15 provides an overview of three common device setups in display technology that emphasise different technologies employed for achieving evolving full-colour images. Fig. 15(a) exhibits RGB-chip emissive displays, which use single micro-LED (μLED) or OLED chips as subpixels. Displays and lighting applications utilise two distinct technologies: Micro-LEDs (μLEDs) and OLED (Organic Light-Emitting Diode) chips. In this setup, these subpixels also emit light, making up the total display output. Fig. 15(b) outlines the concept of colour conversion (CC) emissive displays. Here, either micro-LEDs, micro-LEDs, or OLED chips can be used as subpixels with color conversion mechanisms implemented. The diagrammatic representation exposes the methods applied to generate full-colour images through means of colour conversion processes. Non-emissive display technology is represented by μLED Backlit LCDs in Fig. 15(c) [204].

This kind of convergence has been a focus in several research works that underline the importance of optimising micro-LED performance and functionality [168,205,206]. Mmuch interest in this is to improve light extraction efficiency, control emission angles, as well as polarisation management. This integration creates the breakthroughs of the micro-LED technology by combining nanomaterials with III-nitride nanostructures [152]. Nanomaterials, like gallium nitride (GaN), are very significant substances not only in micro-LED technology but also for the development of solar energy absorption and energy conversion improvements in the renewable energy industry [207]. The use of nanomaterials in micro-LED technology is based on Molecular Beam Epitaxy (MBE) and Metal-Organic Chemical Vapor Deposition (MOCVD) techniques [208]. This symbiotic relationship between nanomaterials and processing methods, particularly GaN and III-nitride nanostructures, enhances the efficiency of optoelectronic gadgets. These

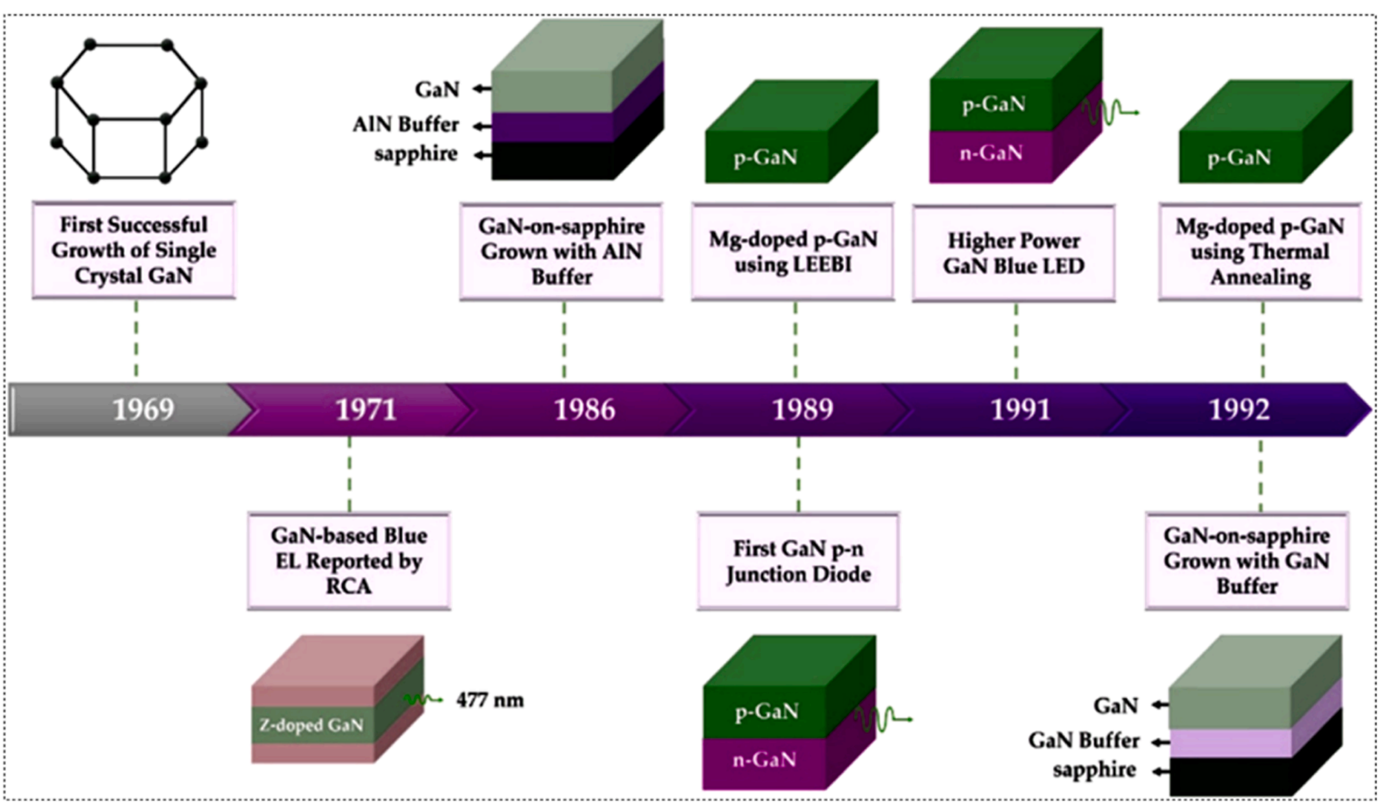

Fig. 13. Timeline of important milestones achieved in the development of the first GaN-based light-emitting p–n junction diode [39].

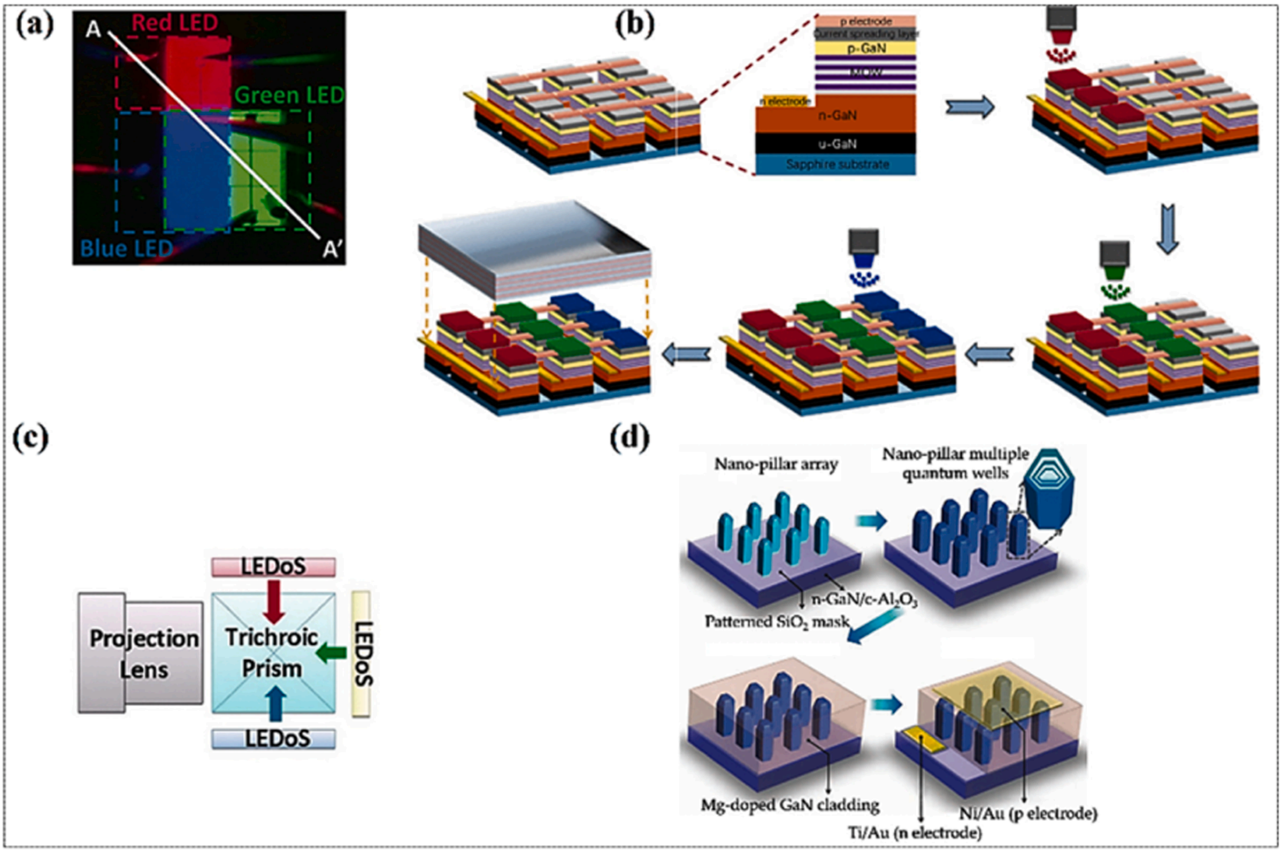

Fig. 14. (a) Image depicting the emission of full-color sub-pixels under a microscope [199], (b) Diagram illustrating the aerosol jet printing technology process [199,200], (c) Diagram depicting the optical setup of a projection system [199,201], (d) Picture detailing the creation and electron microscope view of embedded nano-pillar LED [199,202].

advancements were made possible by Gallium Nitride (GaN), which consists of gallium (Ga) and nitrogen (N) atoms in a crystalline structure [209]. This has translated into remarkable advancements, such as smaller, more flexible, transparent, and energy-efficient micro-LED displays [186]. Significant progress has been made in optimising the performance and functionality of micro-LEDs. This entails integrating III-V LEDs with silicon thin-film transistors, developing multicolor nanocolumn micro-LED pixels, and creating monolithic integrated devices that contain GaN micro-LED with graphene transparent electrodes [210,211]. These III-V LEDs use semiconductors such as Gallium Nitride (GaN), Indium Gallium Nitride (InGaN), and Aluminum Gallium Arsenide (AlGaAs) to produce a wide range of colors for lighting, displays, and optical communications [212,213]. These LEDs exhibit high efficiency across different technology sectors. Thus, the developmental path has been traced from the evolution of gallium nitride (GaN)-based light-emitting diodes (LEDs) to advanced applications, quantum dot integration, and the cooperation with nanomaterials, indicating perpetual development and potentially beneficial opportunities for the future of micro-LED technology [114,214].

5.1. Nanostructures -enhanced micro-LED display technology

Energy-efficient lighting systems have been significantly transformed by high-brightness LEDs and laser diodes, leading to the development of rugged displays and numerous other technological applications. Notably, there have been remarkable advances in GaN-based LEDs and laser diodes, which underline high luminous efficacy and quantum efficiencies [215]. GaN's role in achieving superior performance characteristics in optoelectronic devices is encapsulated by this progress. Kang's [216] investigation into fabrication techniques as well as device architectures for GaN nanostructures intended for LED applications has revealed new and practical applications of GaN, which go beyond the possibilities of traditional thinking[216]. This research provides valuable insights to improve the efficiency of GaN-based LEDs by using nanostructure designs. Zhou et al.'s [217] contribution also focuses on new uses for III-nitrides, such as LEDs, solar cells, power electronics, and magnetic devices[217]. It broadens the understanding of III-nitride materials and their versatility in different technological terrains. The focus of Kente on the synthesis, characterisation, and application of GaN nanostructures underscores their importance, about which they represent a comprehensive view in various scientific and technological areas [218]. This research helps to enhance the foundational knowledge for the optimisation of GaN nanostructures. Kente et al. [218] highlights the fact that GaN has revolutionised wireless communications, radar systems, and power electronics by playing key roles in high-power and high-frequency devices. Shur et al.[219] also stresses that GaN surpasses other materials in terms of its superior characteristics, like electron mobility and sheet carrier concentration, which make it suitable for high-power applications[218]. Khan et al.'s [220] discussion of the potential of GaN based devices for power electronics presents the useful aspects of GaN related to better power electronic systems[220]. As pointed out by Khan et al. [220], growth techniques especially MOCVD and Molecular Beam Epitaxy MBE are fundamental in fabrication progression. These methods allow scientists to create nanostructures that are best suited for certain purposes. GaN power devices will have significant performance benefits over silicon. GaN holds the potential to outperform other current technologies in power-related applications. Ambacher's discussion on growth techniques and applications of Group III-nitrides brings out improvements made through advanced growth methods such as metal-organic

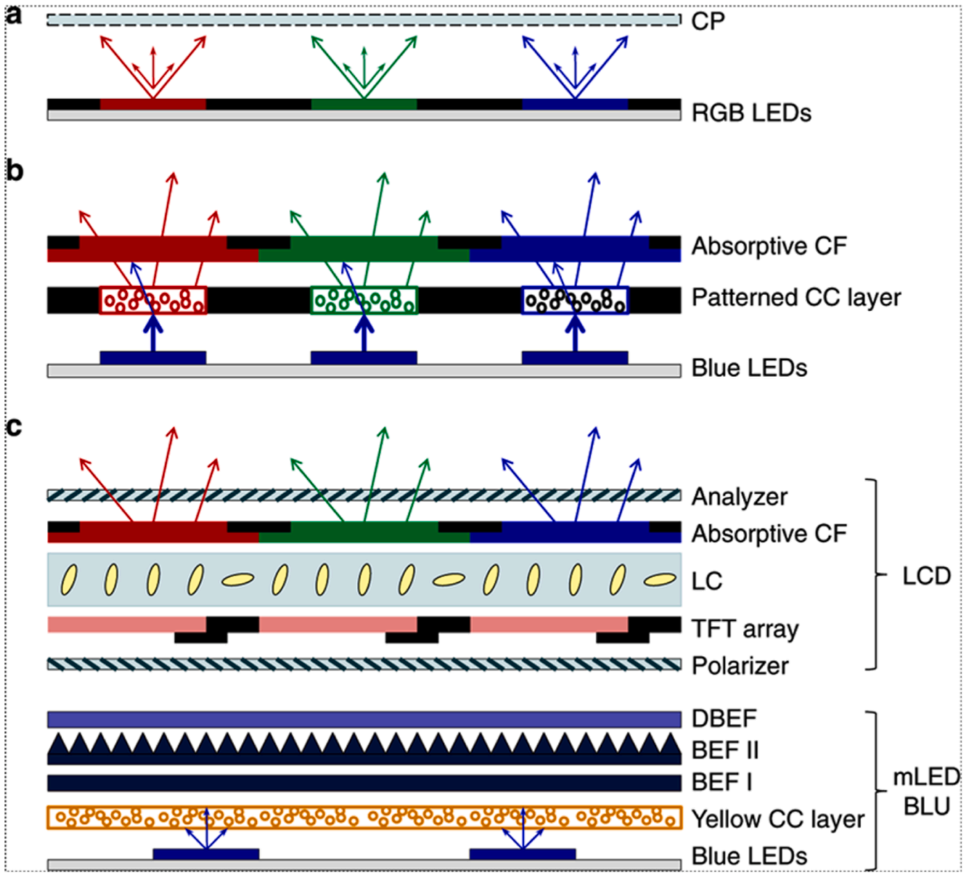

Fig. 15. Three types of displays: (a) RGB-chip emissive displays, (b) Color conversion (CC) emissive displays, (c) mLED-backlit LCDs. In emissive displays (a, b), micro-LED (mLED or μLED) chips act as subpixels. In nonemissive LCD (c), the mLED backlight is structured into zones, each housing multiple mLED chips to manage panel luminance, each zone can be selectively turned on and off [204].

chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) [221]. These insights, in turn, contribute to the constant enhancement of growth techniques for III-nitride materials. Nonetheless, Ambacher et al. [221] has highlighted the challenges in this area, such as minimising material defects, dealing with intricate crystal structures, and curtailing manufacturing expenses[221]. The optimisation of growth processes is crucial to fully harness the potential of GaN and III-nitride nanostructures, necessitating a better understanding of growth mechanisms. It is found that GaN-based LEDs and laser diodes help save energy and improve visual quality [222–224]. These devices are efficient and bright enough, making them important in the development of energy-saving lighting systems. GaN micro-LEDs and Nano-LEDs have been miniaturized, making them versatile enough for the integration of flexible and transparent materials [225–227]. It is a crucial stage toward making these technologies more commercially viable. Production scalability and cost-effectiveness have been improved by several advances in fabrication techniques. These are vital developments towards enhancing the commercial viability of GaN-based LEDs as well as laser diodes. Other than displays, compact LEDs have the potential for automotive lighting and healthcare devices, thereby demonstrating their use in sensing technologies [228,229]. The versatility of GaN-based micro-LEDs and Nano-LEDs is further demonstrated by the widening field of their applications. Advancements in mass production and improvements in display resolutions are some of the key findings from the study on GaN-based micro-LEDs [230]. In spite of notable strides, the issue of crystal defects that affect device performance has remained a central problem. This is vital for commercialisation of high-brightness LEDs and laser diodes [231]. Overcoming these challenges may be resolved by integrating with Si substrates or exploring non-conventional substrates [232]. The approaches give insight into dealing with substrate materials in the best way. The invention of GaN and III-nitride nanostructures has created another level of high-performance LEDs and laser diodes, providing their versatility and potential across a range of technological domains. Contributions by researchers, from basic material synthesis through growth techniques to power electronics and beyond, have enabled the realisation of such devices. The need for continuous improvement in fabrication processes is emphasised by problems associated with growth processes and substrate materials that hinder the full realisation of these materials' potentials. In addition, Table 3 provides information about RGB micro-LED development, materials, and methods.

Enhanced luminous extraction, reduced inner losses, and precise control of emitted light are crucial functions of nanomaterials like quantum dots and nanocrystals. Micro-LED displays have their light-emitting qualities optimised by quantum dots and nanocrystals [283]. This synthesis leads to higher brightness, improved color accuracy, and a wider gamut, resulting in a better viewing experience. Wu et al. [158], Wu et al. [206], and Jung-El Ryu et al. [70] have also emphasised the effectiveness, as well as the prolonged lifetimes associated with Mini-LED and micro-LED technologies[158]. The recent advancements in thermal management strategies for micro-LED fabrication have led to its enhanced reliability and overall performance [284]. Good thermal management helps maintain the stability of Micro LED displays over time. Not only does the integration of nanomaterials optimise display efficiency, but it also allows for flexible and transparent micro-LED capabilities to be developed [285,286]. There are new opportunities in the fields of curved or bendable screens and transparent displays. When integrating III-V compound semiconductors such as GaN or InGaN with Silicon-based Thin-Film Transistors (TFTs), it is important to ensure compatibility between the materials. Differences in crystal structures

Table 3
Materials/Methods for RGB Micro-LED Development.

Materials/Methods	Remarks	Reference
RGB QDs (CdSe/ZnS, CdS)	RGB QDs emit light at 450 nm, 520 nm, and 630 nm wavelengths when excited by 365 nm ultraviolet light.	[233]
Full-color micro-LED array	Resolution: 128 × 128, Pixel size: 35 μm, Pixel pitch: 40 μm. Applied in displays and visible light communication.	[233]
Nanowire Heterostructures	Advantages include reduced dislocation density, polarisation field, improved light extraction efficiency, and compatibility with silicon substrates.	[4,234, 235]
Core/Shell GaN Nanowire Array	Core/shell GaN nanowire LED with modulatable emission wavelength by external voltage.	[236]
Dot-in-a-Wire Nanowire with QDs	Nanowire LED containing QDs (dot-in-a-wire) allowing efficient emissions across the visible wavelength range.	[237,238]
Nanowire LED Arrays via SAG Technology	Nanowire LED arrays with diameters as small as 150 nm prepared through selective area growth (SAG) technology.	[239,240]
Nano-Ring (NR) Structure for RGB LEDs	Implementation of nano-ring structure for tunable emission wavelength and monolithic RGB micro-LED array with red QDs.	[241,242]
Photolithography and Photoresist	Anti-crosstalk window mold with window for QD injection and silver-plated barrier wall.	[243]
Microwave-Assisted Heating	QD solution prepared with a microwave-assisted heating method, resulting in enhanced quantum yield.	[244]
Salt-Sealed QD	RGB color conversion film using salt-sealed QDs for improved reliability and service life.	[245]
Photoresist Hybrid QD	Patterning multi-color QD arrays using a photoresist hybrid, providing a cost-effective solution.	[246]
Photoresist Color Conversion	RGB full-color micro-LED array using a photoresist color conversion layer mixed with QD, achieving high QY.	[10]
Black Matrix Photoresist Spacers	Monolithic RGB QD micro-LEDs with black matrix photoresist spacers for improved light efficiency.	[247]
Funnel Tube Array	Funnel tube array structure for micro-LED display color conversion, reducing color crosstalk and improving efficiency.	[248]
Nanoporous (NP) GaN Structure	NP GaN structure for QD color conversion, improving structural stability and light absorption rate.	[249,250]
Light Emitting Diodes Projector	RGB three-color micro-LED array on silicon with a trichroic prism for a full-color projection system.	[251,252]
ZnCdSe/ZnCdMgSe multi-quantum-well color-converting membrane	Transfer of color conversion film to micro-LED, demonstrating hybrid micro-LED emission.	[253]
InGaN Epitaxial Structure	Micro-LED array with a high In content of up to 0.4, enabling programmable dynamic image display.	[254]
Carrier Blocking Layer (ICBL)	ICBL inserted between multiple QWs in different active regions to guide carriers and improve luminous efficiency.	[255]
GaN, Mg-based p-doping, InGaN Epitaxial growth, GaN-on-sapphire substrates	Enabled development of GaN-based LEDs, Blue emission achieved.	[255–257]
InGaN, p-GaN/n-InGaN/n-GaN DH High-quality growth, Active region of first GaN-based blue LED	Output power: 125 μW, EQE: 0.22%.	[258]
Commercial blue LED by Nakamura et al.	p-AlGaN-based EBL to prevent carrier overflow. Output power: 1.5 mW, EQE: 2.7%, λ: 450 nm.	[259]
InGaN quantum well-based blue, green, yellow LEDs	Single-quantum-well devices, Basis for first-generation nitride LEDs. EQE values of 9.1%, 6.3% at blue, green emission wavelengths.	[260]
Substrates: GaN-on-sapphire, semi- and non-polar substrates	Advancements in epitaxial growth techniques. Focus on low-dislocation density GaN substrates, Semi- and non-polar substrates for improved performance.	[261–263]
Non-polar m-plane bulk GaN substrate	Development of high-performance blue LED. Output power: 0.24 mW, EQE: 38.9%.	[264]
Patterned sapphire substrates (PSS)	Low-power blue LEDs, Maximum EQE of 85%, WPE of 81.3%. Development of low-power blue LEDs with PSS.	[265]
Quasi-bulk GaN substrates	High-power violet LEDs, Peak EQE of 73%. Development of high-power violet LEDs with quasi-bulk GaN substrates.	[266]
Flip-chip (FC) technique, Pattered sapphire substrate, Volumetric bulk GaN substrates	Techniques to enhance light extraction efficiency. FC technique enhances LEE by substrate removal, PSS improves LEE, Volumetric bulk GaN substrates achieve 90% LEE.	[266,267]
Modulation-doped AlGaN/GaN heterostructure	Enhancement of effective hole concentration. Improved conductivity and current spreading characteristics.	[268]
AlGaN/GaN high electron mobility transistors (HEMTs)	Utilisation of modulation doping for nitride devices. Promotion of sheet carrier densities in the order of 10^{13} cm^{-2} in nitrides.	[169]
GaN-based LEDs for solid-state lighting (SSL)	Disruptive technology in lighting, White LEDs, Ce: YAG phosphor. Commercialisation of first white LED in 1996 by Nichia Corporation.	[269,270]
RGB nitride LEDs for white light	Direct combination of red, green, and blue LEDs. Potential for highest luminous efficacies, RGB arrays on a single chip.	[271]
Nitride-based UV LEDs	AlGaN-based UV LEDs, Tunable bandgap. Applications in air and water purification, sterilisation, bio and environmental sensing.	[272,273]
III-nitride micro-LEDs	Development for wearable, portable, and futuristic displays. Emerging technology for high-resolution display applications.	[188,274]
Nitride LEDs for Visible Light Communication (VLC)	High-frequency LEDs, VLC systems. Sub-100 μm LEDs for ultra-broadband VLC protocols.	[275–279]
Cryogenic Operation of Nitride LEDs	Asymmetric carrier freeze-out, Polarisation-induced doping. Challenges and techniques for optimising nitride LEDs at or near-cryogenic temperatures.	[280–282]

and properties can make seamless integration difficult to achieve. TFTs are an example of special transistors, which are widely used in the electronics industry, for instance, in making flat panel displays such as LCDs (Liquid Crystal Displays) and OLEDs (Organic Light Emitting Diodes) [212,213]. The confluence of wide-bandgap semiconductors, particularly for LEDs and GaN-based lasers, has various roles to play [284]. With these devices being integrated together, there will be versatile wide-bandgap semiconductor integrated circuits that enhance overall performance and functionality across electronic and optoelectronic domains [284] [287]. Detailed summaries of wide-bandgap semiconductors based on materials, devices, and application perspectives can be found in Fig. 16 [286]. GaN nanostructures have been a major breakthrough, as seen by the success of N-polar InGaN/GaN nanowire green and red LEDs with high efficiency [286] [176,177]. Gallium Nitride (GaN) nanostructures have been highly impactful, particularly demonstrated by the success of high-efficiency N-polar Indium Gallium Nitride/Gallium Nitride (InGaN/GaN) nanowire green and red Light-Emitting Diodes (LEDs) [288,289]. The N-polar orientation, characterised by lateral dimensions as small as 0.7 µm, plays a pivotal role in achieving a flat top surface morphology, rendering these structures highly compatible with fabrication technologies. Notably, the development of an in-situ annealing method for nanowires exhibiting strong red emission has resulted in a remarkable order of magnitude increase in nanowire luminescence [288]. Transitioning to the domain of Ultraviolet (UV) micro-LEDs, their anticipated advantages are tempered by persistent efficiency challenges. Factors such as crystal quality, high-quality p-type Aluminum Gallium Nitride (AlGaN) layers, and UV light absorption have been identified as critical limiting elements [205,290]. This recognition underscores the significance of addressing these challenges to fully harness the potential benefits of UV micro-LED technology, encompassing high efficiency, reliability, fast modulation speed, low cost, and low power consumption. In parallel, the progress in red micro-LEDs, specifically those based on InGaN, has outpaced standard-sized Aluminum Gallium Indium Phosphide (AlGaInP)-based red LEDs in terms of luminous efficiency [161,291,292].

Quantum dots and nanocrystals still play a pivotal role in optimising light extraction, minimising internal losses, and enabling precise control of emitted light. The exploration of quasi-2D Ruddlesden—Popper perovskites (2D-RPPs) is a promising way to achieve deep blue color in LED displays [294]. These perovskites can overcome challenges through fast crystallisation, leading to possibilities for improved vividness and quality displays. Quasi-2D Ruddlesden—Popper perovskites represent an intermediate class between conventional 3D and purely 2D perovskite structures. Perovskites are materials that have gained a lot of interest due to their unique crystal structure and a wide range of applications, especially in optoelectronics such as solar cells and light-emitting devices. In the perovskite family, the Ruddlesden—Popper phase or type refers to a layered structure [295]. Large-scale manufacturing of III-V LEDs with silicon TFTs and perovskite LEDs is challenging. For the advancement of such modern display technologies, it is necessary to develop new fabrication techniques [296]. One-way breakthroughs are made to improve the stability of perovskite LEDs involves using a dipolar molecular stabiliser. This innovation results in highly effective and durable perovskite LEDs that can last a long time, thereby addressing questions about the durability of advanced display technologies. Long-term operation tests, as well as accelerated aging experiments, provide useful information about the functional behavior and reliability of perovskite LEDs under operation. To obviate typical flaws found in the top-down LED design, plasma etching is not required when nano or micro-LEDs are developed through a bottom-up method. This helps avoid surface defects common in conventional top-down LEDs, although they remove the need for plasma etching. Improved charge carrier recombination quantum efficiency of

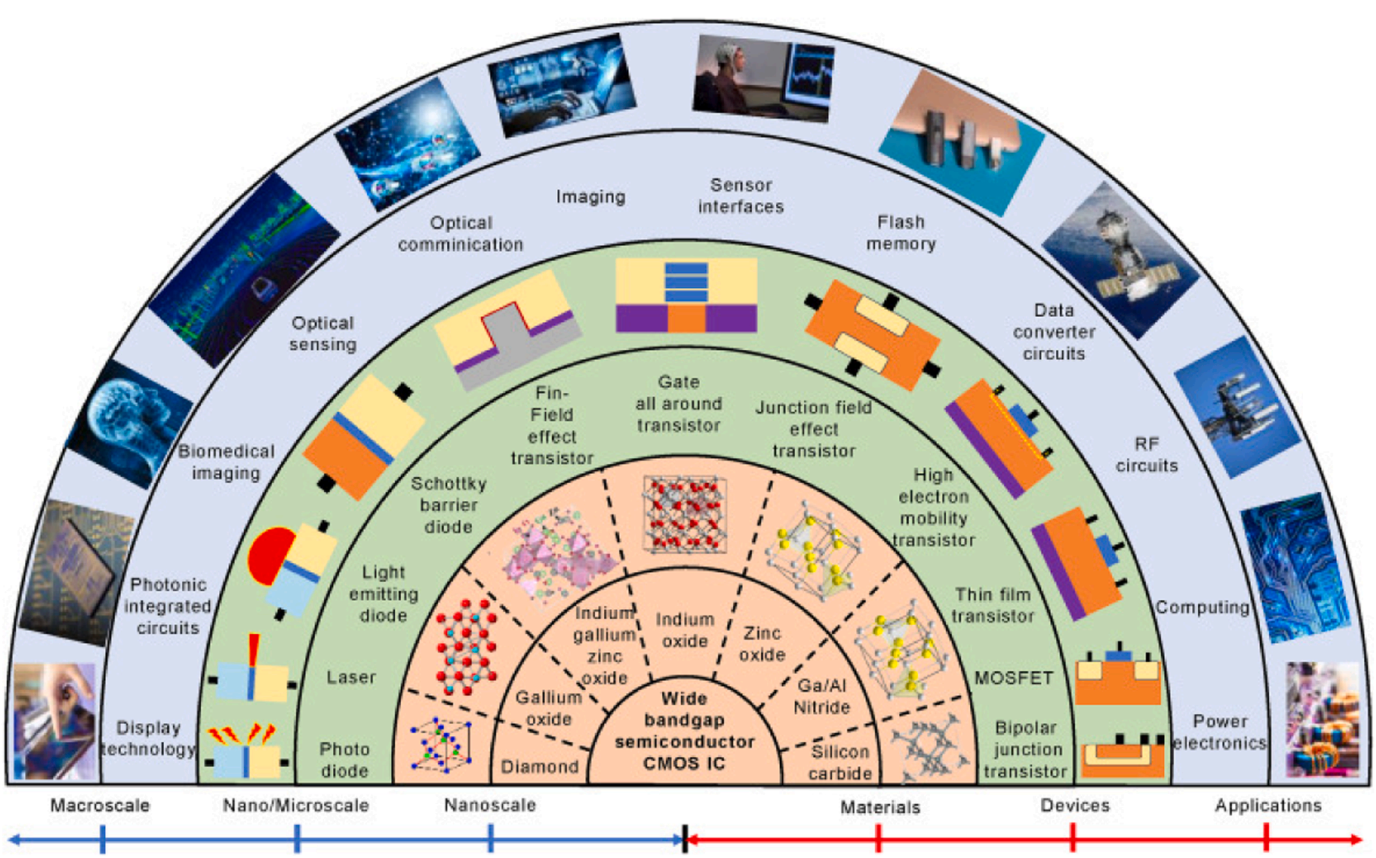

Fig. 16. Detailed summary of wide bandgap semiconductors based on materials, devices, and application perspective[293].

dislocation-free crystal growth on various substrates is facilitated by metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) [235,297]. Strain relaxation enhances dopant incorporation, which is important for maximising injection efficiency in LEDs [298,299]. A core-shell structure resulting from wide-bandgap AlGaN incorporation in InGaN nanostructures shields the active region from surface recombination effects. Precise definition of nanostructure dimensions, shape, morphology, and placement before epitaxy can be achieved using selective area epitaxy (SAE) with both MBE and MOCVD [300,301]. Hence, growing crystals only in exposed substrate areas allows the production of desired tailored nanostructure arrays. Multi-color pixels and micron-scale platelets, pyramids, nanowires were reported by Kishino et al.'s studies [302]. Recent research by Wang et al.[303], [37,304]however, demonstrated green LED matrices with a peak EQE of ~9% and red-emitting micro-LEDs with a peak EQE of 1.75%, both grown utilising selective area epitaxy [37,304]. For instance, an integration between a micro-LED and a high-electron-mobility-transistor (HEMT) resulted in a modulation bandwidth of 1.2 GHz, which is the highest ever recorded in this context [305]. By arranging nanostructures in certain configurations, photonic crystals or metasurfaces can be created to enhance emissions. It is possible to design the photonic crystal to increase light extraction efficiency, direct emission, and reduce spectral broadening. This strategy has found application in nanostructure-based surface-emitting lasers, specifically photonic crystal surface-emitting lasers (PCSELs) [180,306]. The LED technology is depicted in Table 4 through the revolution from GaN nanostructures to Ultraviolet (UV) micro-LEDs and the rapid advancement of InGaN-based red micro-LEDs. Such technologies are exemplified by key nanomaterials, their properties, and fabrication details of nanostructures for micro-LED technologies, as indicated in Table 4. High efficiency, spectral line width, among others, are some of the main properties that highlight their importance in micro-LED technologies. The activities encompass MOCVD growth, ALD, and PECVD processes, which are useful for on-wafer packaging advances and addressing issues arising with regard to material quality.

5.2. Perovskite mini-micro–LED stability and efficiency

A significant milestone has been recorded in the field of display technology by the Perovskite LED (Light-Emitting Diode) technology, thereby demonstrating momentous advancement. The unique crystal structure (ABX_3) used to build these LEDs has some benefits like high color purity, adjustable bandgap, and ease of making [323]. Of all the materials available, metal-halide perovskites that possess optoelectronic features akin to those of III-V materials have demonstrated potential for application in light-emitting diodes (LEDs) [324,325]. Among the organic halide perovskite quantum dots (OPQDs), scientists are actively tackling the challenge of lattice instability and surface defects in metal halide perovskites (MHPs) [326]. There are new methods being explored such as F anion doping to increase stability [327]. Furthermore, it is used as a protective shield against lattice decomposition when applying SiO_2 coating. Specifically, $CsPbBr_3$:KBF_4@SiO_2 nanocrystals (NCs) exhibit good stability along with 85% photoluminescence quantum yield (PLQY) [328] [329]. Perovskite LED breakthroughs and structural insights are found in Fig. 17, indicating the relationship between structural characteristics and stability/performance improvements. As depicted in the upper left panel of Fig. 17, the perovskite LED structure comprises detailed intricate elements. The right-hand panel of the Figure presents a graph representing T50 lifetimes of LEDs with respect to their optical power output (radiance) [296].

Numerous long-term stability tests and accelerated aging were performed to glean insights on the durability of perovskite LEDs. Stability data is summarised in Fig. 18, which encompasses the findings from all these experiments. The left panel presents results of long-term operation and accelerated aging experiments, while the right panel offers external quantum efficiency data, aiding in comprehending efficiency

Table 4
Overview of nanostructures for micro-LED technologies.

Nano Materials	Properties	Remarks	References
N-polar InGaN/GaN nanowire arrays	High efficiency (EQE up to 25%), lateral dimensions as small as 0.7 µm	N-polar orientation yields flat top surface, compatible with fabrication. Reversed polarisation reduces electron overflow. In-situ annealing enhances red emission in nanowires.	[172,288,289]
InGaN photonic crystal nanowire	Spectral linewidth of 4 nm, one order of magnitude smaller than conventional quantum well LEDs	Enables individually addressable pixel illumination, bringing maskless photolithography possibilities.	[183,307]
Novel micro-LED structure design with quantum dots (QD)	Anti-crosstalk solution	Optimal optical design using Monte Carlo method, addressing crosstalk problem, and introducing chip micro-LED + QD fluorescence mode	[308]
GaN-based micro-LED arrays with tailored fluorine ion implantation	Improved uniformity, reduced leakage currents	Pixelation strategy using F ion implantation, multi-energy injections for uniformity, and reduced reverse leakage currents	[309]
InGaN/GaN multiple quantum wells micro-LEDs with piezo-phototronic effect	Strain visualisation, color response	Dual-wavelength micro-LEDs demonstrating strain visualisation, significant color response under mechanical stimulation	[310]
GaN-based micro-LEDs with ion implantation	Improved luminous efficiency, reduction of surface defects	Ion implantation method to modify sidewall surface defects, enhanced photoelectric performance, increased external quantum efficiency (EQE)	[311]
SiO_2-coated CdSe/ZnS quantum dots	Photoluminescence enhancement, fluorescence decay reduction	Synthesis of SiO_2-coated CdSe/ZnS QDs with tunable emission wavelengths, improved PLI and decay rate, integration into photoresist for micro-LED display, design of a DBR layer for full-color micro-LED display	[312]
Nickel oxide nanoparticles (NiO NPs)	Adjustable optoelectronic properties, high photosensitivity and detectivity for UV photodetector	Synthesis using co-precipitation, precursor concentration effects studied, high photosensitivity and detectivity, high photosensitivity (1100%) and specific detectivity (4.324 × 10−10 Jones) for	[313]

(continued on next page)

Table 4 (*continued*)

Nano Materials	Properties	Remarks	References
		diode evaluated at 120 mW/cm^2	
Quantum dots (QDs) in metal/oxide/semiconductor junction (LE-MOSJ)	Ultrahigh-resolution display (4200 PPI), simple structure of ITO/Al_2O_3/QDs/Ag	Proposed QD-based light-emitting MOS junction (LE-MOSJ) with sub-10 micrometer device array, achieves ~4200 PPI LE-MOSJ array	[314]
Aligned s-CNT array (A-CNT)	High mobility, large driving current	A-CNT TFTs for mLED/μLED backplanes with exceptional performance, surpassing commercially available TFTs	[315]
SrCeO3:Eu3+ nanopowders	Orthorhombic structure, red emission	Versatile red-emitting SrCeO3: Eu3+ nanopowders for displays and forensic applications	[316]
Nanocrystals in glasses	High-throughput, thermally stable, micrometer-scale luminescent patterns	Laser-induced inverted patterning for micro-LED color conversion layers	[317]
Poly(methyl methacrylate) (PMMA) resist patterns in micro-nanoscale	Uniform, reproducible micro-nanoscale patterns	AFM mechanical ploughing for cost-effective fabrication of OLED arrays with pixels of 500 nm and 1 μm	[318]
GaN-on-Si micro resonantbased blue micro light emitting diodes	Improved characteristics, reduced sidewall damage	Ion implantation and resonant cavity structure in nanorange for enhanced stability and optical characteristics in GaN-based micro-LEDs	[319]
GaN-related quantum wells	Correlation between photoluminescence and electroluminescence in GaN-related micro-LEDs	Systematic analysis considering carrier escape, applied bias, leakage current, incident light absorption, and carrier accumulation	[320]
SiO_2-coated perovskite quantum dots	Luminous properties preservation, color conversion	Synthesis of cadmium-free perovskite QDs with SiO_2 passivation, application in blue micro-LED display, improved color purity using distributed Bragg reflector (DBR)	[321]
Perovskite nanocrystals (PNCs)	PNC-polymer composites with superhydrophobic surface for stable and efficient white LEDs	Highly luminescent PNC-polymer composites with superhydrophobic surface, enhanced chemical stability, improved out-coupling efficiency	[322]

improvements [296] [18]. The use of light emitting diodes based on LTA zeolite with quantum dots (QDs) of $CsPbBr_3$ has been demonstrated to be stable and possess high photoluminescence quantum yield (PLQY) [329,330]. This study demonstrates that incorporating QDs into zeolites may lead to high stability over a wide range of optical properties in perovskite-based systems. In this regard, a novel method has been introduced for fabricating continuous perovskite films using high-resolution micro-patterning technique. Ultra-high-resolution displays (UHDs) can be achieved cost effectively by employing PeLEDs [331]. One-pixel PeLEDs which have effective area dimensions of 500 × 200 μm^2 to 100 × 200 μm^2, and exhibit EQE values as high as 9.1% are a reality now. A Lithium fluoride thin film interlayer in the nanometer scale is the key for such success because it relieves surface tension and makes possible robust integration of high-efficiency PeLED architectures via self-aligned photolithography [332].

Notwithstanding remarkable advancements in research on PeLEDs, the attainment of efficient PeLED micro-sized pixels remains an unsolved issue. Recent investigations have found EQEs that are above 20% and IQEs close to 100% [333,334]. There is limitation in options for improved emission efficiency from micropatterned emissive arrays in PeLEDs hence this becomes a barrier to further improvements [335,336]. Advances in perovskite mini-micro–LEDs have demonstrated great promise in terms of stability and efficiency. This field has seen major developments due to path-breaking strategies, materials, and fabrication techniques. At the same time, challenges and ongoing work indicate that perovskite-based LED technologies continue to seek better performance.

6. Commercialisation challenges and applications of micro-LED development

Obstacles to the commercial viability of small-area micro-LEDs include challenges in efficiency, particularly for InGaN variants using green and red. Emission characteristics, quantum efficiency, and color stability are negatively affected by irregular indium distribution. Current research is directed towards advancing material engineering to achieve precise indium control, a key factor for highly efficient colors. Reduced quantum efficiency due to crystal defects like dislocations in III-nitride nanostructures underscores the need for defect mitigation to improve crystal quality. Improved growth techniques are required to reduce defects while enhancing the structural integrity of III-nitride nanostructures [304,337]. In spite of these hurdles, III-nitride nanostructures, especially gallium nitride (GaN), hold great promise across various applications [338]. Marketable products are made from the discoveries in nanotechnology, but they face many obstacles, such as high initial production costs [338]. To make it in the competitive domain of advanced materials, startups require strategic alliances [339]. Nitride development success is dependent on managing technical challenges and making wise choices of substrates that can be scaled up and be cost-effective [340]. The possible solution to this challenge is explored by examining bulk GaN growth. This will be done through optimising crystal growth parameters, developing cutting-edge techniques, and gaining more insight into the underlying processes. Ultimately, this will lead to enhancing the efficiency and scalability of gallium nitride (GaN) production, which will then result in better device performances and cost-effectiveness [341]. The need for the standardisation of protocols in quality control for III-nitride microelectronic devices can never be overstated. To ensure uniformity, reliability, and consistency in manufacturing, these aspects are highly critical. Precise measuring capabilities and reproducibility are provided by them, while benchmarking through addressing issues of variability further enhances the overall quality of devices [342]. Zhao et al. [343] explores unconventional substrate growth for III-nitride nanowires, introducing innovative design possibilities[343]. Pandey et al. [344] focuses on III-nitride nanostructures for high-efficiency micro-LEDs and optoelectronics, bringing advantages such as enhanced efficiency, precise wavelength control, durability, compact size, wide bandgap for efficient light emission, versatility in design, energy efficiency, compatibility with semiconductor processes, and contribution to technological advancements[344]. In this case, Dehghani et al. [345], Galbraith et al. [346], and Arora et al. [347] have all underlined the importance of commercialisation in nanotechnology as a potential source of economic growth requiring efficient technology transfer and adaptation to market

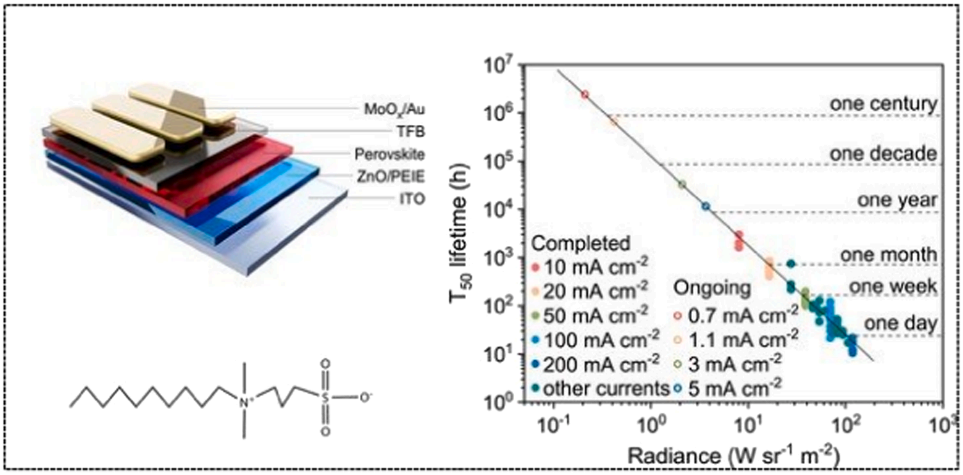

Fig. 17. Structural insights into the perovskite LED are presented in the upper left panel, the right panel of the figure displays a graph illustrating the T50 lifetimes of the perovskite LEDs in relation to their optical power output (radiance)[296].

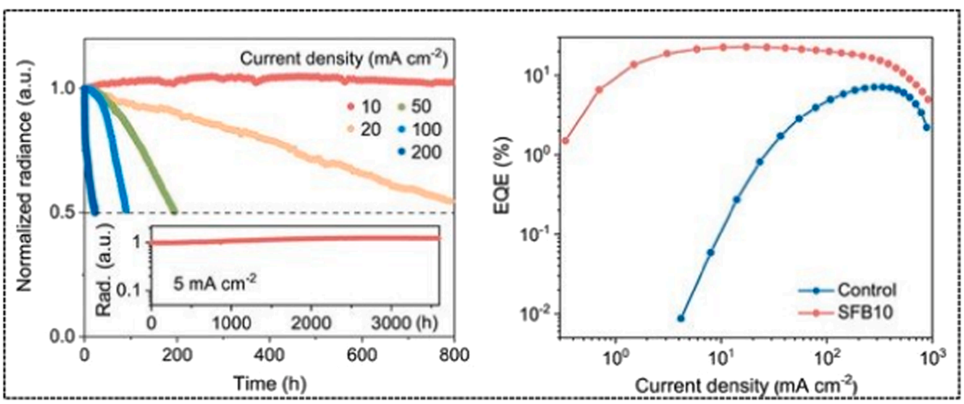

Fig. 18. The left panel of this figure illustrates the results of long-term operation and accelerated aging experiments conducted on the perovskite LEDs. The right panel of the figure displays external quantum efficiency data, comparing the stabilised devices with untreated ones[18].

demand. Teece et al. [348] argues that there is a need for continued investment in Research and Development for refining micro-LED technology (MLED), [348]which has the potential to provide better display quality, be energy saving and versatile [349]. The efficiency challenges associated with large-scale manufacturing using pick-and-place techniques are recognised; thus, ongoing investigations are focusing on developing highly scalable robotics systems and automated processes [350]. This addresses issues such as: hurdles in efficient assembly, full-color schemes, defect management and cost control [351]. Mass transfer problems and manufacturing costs should be resolved [157]. Micro-LEDs have a huge potential to change our visual experience. Chen et al. [352] emphasises that mass transfer techniques for high-density micro-LED arrays are important[352]. Furthermore, the work of Bower et al. [353] focuses on high-brightness displays using micro-transfer printed flip-chip micro-LEDs[353]. Conversely, Zhou et al. [354] addresses growth, transfer printing, and colour conversion techniques for full-color micro-LED displays[354], including the challenges involved in achieving uniform color distribution, managing defects, and optimising cost-effectiveness [355]. On the other hand, integration challenges for micro-LEDs include defect management, improving yield rates, and balancing efficiency and scalability [356] [357]. However, Ahmed et al. emphasises the importance of epitaxy costs, transfer and defect management 351]. Also useful are Lee et al.'s [356] views on the potential of micro-LED technologies for high-performance emissive displays[356], as well as Cok et al.'s [358] explanation about the benefits of micro-transfer printing in creating inorganic micro-LED displays[358]. The integration of manufacturing techniques and automation can be helpful. High-quality displays cannot do without quality control protocols and defect management systems. Currently, the study is aimed at optimising the production processes, enhancing mass transfer effectiveness, and improving integration approaches. It is important for micro-LED manufacturing to emphasise automation optimisation to achieve cost-effectiveness and efficiency [359]. Tape assisted Laser Forward Transfer (TALFT) process for high-accuracy wafer-scale micro-LED transfer has been considered by research [151], while fluid self-assembly suggested by Ji et al. [360] as a different approach for transfer of micro-LEDs[360]. These benefits show that micro-LED possesses many positive traits such as longevity, high efficiency among others [361]. The challenge now is to make nanoLEDs work with pixel sizes of all sizes [362]. Li et al.'s [363] research shows that this technology could develop Mini-LED products with low power consumption and high reliability [151,363]. LED chip fabrication, as well as placement uniformity and cost-efficiency, is also hampered by Ryu et al. [70]. On the other hand, quantum dots and phosphors are confronted with various challenges, including low conversion efficiency as well as potential toxicity [214,364]. While there are obvious benefits to using quantum-dot-based color conversion, it leads to more layers in the manufacturing stage. However, despite this long-term inefficiency, III-nitride inorganic devices, particularly micro-LEDs, continue to be impressive [46,365]. Among several other approaches, like tunnel junction devices and excitonic LEDs that are based on nanostructures [146,366]. For example, in the presence of diverse applications beyond display screens, such as those based on nanostructures for micro-LEDs, may hold significant potential. Optical interconnects that use micro-LED technology promise low-power and high bandwidths to overcome limitations posed by electrical links over long distances [367,368]. Micro-LEDs display a combination of features for use as biological sensing devices that are capable of harvesting energy wirelessly and transmitting signals [369]. In imaging dyes, fluorescence spectroscopy, and neuronal stimulation, nitride-based micro-LEDs are applied [370]. The flexible nanostructure-based approach opens the way for developing distinctive micro-LEDs for specialised applications. Nanostructures are central to overcoming the hurdles faced in nanoscale and micron-scale optoelectronic devices. This makes the selective-area epitaxy method more effective towards the bottom-up formation of photonic crystals [371,372]. Strain relaxation efforts and the suppression of parasitic recombination in SPSL layers are targeted at red-emitting micro-LEDs. To overcome efficiency droop in red-emitting micro-LEDs, the AlGaN electron blocking layer is examined. Tunnel junction contacts may also be used in N-polar devices grown via selective area epitaxy [373–375]. The droop effect of nanowire micro-LEDs at higher injection currents remains problematic. Narrow-linewidth, spectrally pure, high-efficiency micro-LEDs can be achieved on a single chip through integration into photonic crystals in optimised devices. The sensitivity of nanostructures to dimensions emphasises the need for precise substrate control prior to epitaxy and meticulous fabrication post-epitaxy. Ionicity in polar semiconductors, such as InGaN, affects electronic, optical, and excitonic properties. Studies have shown that the exciton binding energy increases dramatically in nanoscale III-nitride heterostructures compared to bulk ones[376,377]. Polaronic excitons, with a binding energy as large as 190 meV in GaN nanowires, illustrate the interaction of excitons with phonons, affecting charge carrier transport, relaxation, and recombination [378]. However, challenging it is, micro-LED technology has several advantages, including display quality and energy efficiency, that, coupled with its versatile applications and ongoing advancements, make it promising for the future of display technology.

7. Concluding remarks

The paper reviews advanced display techniques and explores the opportunities prevalent in this area. In the realm of micro-LED displays, the incorporation of nanomaterials, particularly focusing on nanocrystals and quantum dots, represents a significant leap in display efficiency, color accuracy, and resolution. This advancement holds potential benefits for industries such as electronics, healthcare, and automotive. The integration of III-nitride nanostructures into micro-LEDs contributes to high brightness levels and low energy consumption rates. However, successful commercialisation faces challenges related to scalability, cost-effectiveness, and standardisation. Another approach to consolidating multiple functions into one chip, simplifying system configuration and reducing space requirements, is through Monolithic Integrated Device (MID) technology. Pervasive use of MID technology can be seen in areas like consumer electronics, healthcare, and industrial control systems. The latest developments concern top-down and bottom-up approaches to micro-LED integration, allowing the merging of III-V LEDs with Silicon Thin Film Transistors (TFTs), well-known for leading towards the most recent improvements in high-performance multifunctional devices with high efficiency. However, some attention must be paid to steps that are necessary for understanding manufacturing complexity, uniformity, and cost-effectiveness in order to have better products. Manufacturing complexity, uniformity, and cost-efficiencies are required before these technologies can fully deliver on their promises. This may eventually bring about a world where markets rely on displays that are not just of high quality but also flexible and power-saving.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgement

Raghvendra Kumar Mishra would like to acknowledge the financial support provided by the UKRI. The research received funding from the Engineering & Physical Sciences Research Council (EPSRC), UK – Ref. EP/R016828/1 (Self-tuning Fibre-Reinforced Polymer Adaptive Nanocomposite, STRAIN comp) and EP/R513027/1 (Study of Microstructure of Dielectric Polymer Nanocomposites subjected to Electromagnetic Field for Development of Self-toughening Lightweight Composites).

SG would like to acknowledge the financial support provided by the UKRI via Grants No. EP/S036180/1 and EP/T024607/1, Hubert Curien Partnership Programme from the British Counsil and the International exchange Cost Share award by the Royal Society (IEC\NSFC\223536).

References

[1] A. Chitnis, C. Chen, V. Adivarahan, M. Shatalov, E. Kuokstis, V. Mandavilli, J. Yang, M.A. Khan, Visible light-emitting diodes using a-plane GaN-InGaN multiple quantum wells over r-plane sapphire, Appl. Phys. Lett. 84 (2004), https://doi.org/10.1063/1.1738938.
[2] A. Pandey, M. Reddeppa, Z. Mi, Recent progress on micro-LEDs, Light.: Adv. Manuf. 4 (2023), https://doi.org/10.37188/lam.2023.031.
[3] J.H. Oh, Y.J. Eo, H.C. Yoon, Y.D. Huh, Y.R. Do, Evaluation of new color metrics: Guidelines for developing narrow-band red phosphors for WLEDs, J. Mater. Chem. C. Mater. 4 (2016), https://doi.org/10.1039/c6tc02387h.
[4] H.-M. Kim, Y.-H. Cho, H. Lee, S.Il Kim, S.R. Ryu, D.Y. Kim, T.W. Kang, K. S. Chung, High-brightness light emitting diodes using dislocation-free indium gallium nitride/gallium nitride multiquantum-well nanorod arrays, Nano Lett. 4 (2004) 1059–1062, https://doi.org/10.1021/nl049615a.
[5] R.K. Mishra, J. Cherusseri, A. Bishnoi, S. Thomas, Nuclear Magnetic Resonance Spectroscopy. in: Spectroscopic Methods for Nanomaterials Characterization, Elsevier, 2017, pp. 369–415, https://doi.org/10.1016/B978-0-323-46140-5.00013-3.
[6] R.K. Mishra, J. Cherusseri, E. Allahyari, S. Thomas, N. Kalarikkal, Small-angle light and x-ray scattering in nanosciences and nanotechnology. in: Thermal and Rheological Measurement Techniques for Nanomaterials Characterization, Elsevier,, 2017, pp. 233–269, https://doi.org/10.1016/B978-0-323-46139-9.00010-4.
[7] S.X. Jin, J. Li, J.Z. Li, J.Y. Lin, H.X. Jiang, GaN microdisk light emitting diodes, Appl. Phys. Lett. 76 (2000) 631–633, https://doi.org/10.1063/1.125841.
[8] The Fundamentals and Applications of Light-Emitting Diodes, 2020. https://doi.org/10.1016/c2019-0-00273-7.
[9] Y. Huang, E.-L. Hsiang, M.-Y. Deng, S.-T. Wu, Mini-LED, Micro-LED and OLED displays: present status and future perspectives, Light Sci. Appl. 9 (2020) 105, https://doi.org/10.1038/s41377-020-0341-9.
[10] S.-W.H. Chen, Y.-M. Huang, K.J. Singh, Y.-C. Hsu, F.-J. Liou, J. Song, J. Choi, P.-T. Lee, C.-C. Lin, Z. Chen, J. Han, T. Wu, H.-C. Kuo, Full-color micro-LED display with high color stability using semipolar (20-21) InGaN LEDs and quantum-dot photoresist, Photonics Res 8 (2020) 630, https://doi.org/10.1364/PRJ.388958.
[11] P. Pust, V. Weiler, C. Hecht, A. Tücks, A.S. Wochnik, A.K. Henß, D. Wiechert, C. Scheu, P.J. Schmidt, W. Schnick, Narrow-band red-emitting Sr[LiAl3 N4]:Eu2+ as a next-generation LED-phosphor material, Nat. Mater. 13 (2014), https://doi.org/10.1038/nmat4012.
[12] M. Shang, J. Wang, J. Fan, H. Lian, Y. Zhang, J. Lin, ZnGeN2 and ZnGeN2:Mn2+ phosphors: hydrothermal-ammonolysis synthesis, structure and luminescence properties, J. Mater. Chem. C. Mater. 3 (2015), https://doi.org/10.1039/c5tc01864a.
[13] F. Muñoz, A. Saitoh, R.J. Jiménez-Riobóo, R. Balda, Synthesis and properties of Nd-doped oxynitride phosphate laser glasses, J. Non Cryst. Solids 473 (2017), https://doi.org/10.1016/j.jnoncrysol.2017.08.005.
[14] R.K. Mishra, M.G. Thomas, J. Abraham, K. Joseph, S. Thomas, Electromagnetic interference shielding materials for aerospace application. in: Advanced Materials for Electromagnetic Shielding, Wiley,, 2018, pp. 327–365, https://doi.org/10.1002/9781119128625.ch15.
[15] E.L. Hsiang, Z. Yang, Q. Yang, Y.F. Lan, S.T. Wu, Prospects and challenges of mini-LED, OLED, and micro-LED displays, J. Soc. Inf. Disp. 29 (2021), https://doi.org/10.1002/jsid.1058.
[16] H.X. Jiang, J.Y. Lin, Nitride micro-LEDs and beyond - a decade progress review, Opt. Express 21 (2013) A475, https://doi.org/10.1364/OE.21.00A475.
[17] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, H. Morkoç, Micro-LEDs, a Manufacturability Perspective, Appl. Sci. 9 (2019) 1206, https://doi.org/10.3390/app9061206.

[18] B. Guo, R. Lai, S. Jiang, L. Zhou, Z. Ren, Y. Lian, P. Li, X. Cao, S. Xing, Y. Wang, W. Li, C. Zou, M. Chen, Z. Hong, C. Li, B. Zhao, D. Di, Ultrastable near-infrared perovskite light-emitting diodes, Nat. Photonics 16 (2022) 637–643, https://doi.org/10.1038/s41566-022-01046-3.

[19] C.-C. Lin, Y.-R. Wu, H.-C. Kuo, M.S. Wong, S.P. DenBaars, S. Nakamura, A. Pandey, Z. Mi, P. Tian, K. Ohkawa, D. Iida, T. Wang, Y. Cai, J. Bai, Z. Yang, Y. Qian, S.-T. Wu, J. Han, C. Chen, Z. Liu, B.-R. Hyun, J.-H. Kim, B. Jang, H.-D. Kim, H.-J. Lee, Y.-T. Liu, Y.-H. Lai, Y.-L. Li, W. Meng, H. Shen, B. Liu, X. Wang, K. Liang, C.-J. Luo, Y.-H. Fang, The micro-LED roadmap: status quo and prospects, J. Phys.: Photonics 5 (2023) 042502, https://doi.org/10.1088/2515-7647/acf972.

[20] Z. Liu, C.-H. Lin, B.-R. Hyun, C.-W. Sher, Z. Lv, B. Luo, F. Jiang, T. Wu, C.-H. Ho, H.-C. Kuo, J.-H. He, Micro-light-emitting diodes with quantum dots in display technology, Light Sci. Appl. 9 (2020) 83, https://doi.org/10.1038/s41377-020-0268-1.

[21] K. James Singh, Y.-M. Huang, T. Ahmed, A.-C. Liu, S.-W. Huang Chen, F.-J. Liou, T. Wu, C.-C. Lin, C.-W. Chow, G.-R. Lin, H.-C. Kuo, Micro-LED as a promising candidate for high-speed visible light communication, Appl. Sci. 10 (2020) 7384, https://doi.org/10.3390/app10207384.

[22] C.-W. Jeon, H.W. Choi, E. Gu, M.D. Dawson, High-density matrix-addressable alInGaN-Based 368-nm microarray light-emitting diodes, IEEE Photonics Technol. Lett. 16 (2004) 2421–2423, https://doi.org/10.1109/LPT.2004.835626.

[23] B.R. Tull, N. Twu, Y.-J. Hsu, S. Leblebici, I. Kymissis, V.W. Lee, 19-1: *Invited Paper*: micro-LED microdisplays by integration of III-V LEDs with silicon thin film transistors, SID Symp. . Dig. Tech. Pap. 48 (2017) 246–248, https://doi.org/10.1002/sdtp.11680.

[24] K. Yin, E.L. Hsiang, J. Zou, Y. Li, Z. Yang, Q. Yang, P.C. Lai, C.L. Lin, S.T. Wu, Advanced liquid crystal devices for augmented reality and virtual reality displays: principles and applications, Light Sci. Appl. 11 (2022), https://doi.org/10.1038/s41377-022-00851-3.

[25] E.-L. Hsiang, Z. Yang, Q. Yang, P.-C. Lai, C.-L. Lin, S.-T. Wu, AR/VR light engines: perspectives and challenges, Adv. Opt. Photonics 14 (2022), https://doi.org/10.1364/aop.468066.

[26] J. Song, J.W. Choi, C. Chen, K. Wang, D. Wu, Application of porous GaN for microLED, in: 2020. https://doi.org/10.1117/12.2545330.

[27] K. Urakawa, H. Onuma, M. Maegawa, K. Kubota, S. Oie, D. Hatakeyama, S. Akase, Y. Ikawa, S. Yamaguchi, N. Momotani, K. Mikami, Y. Fujita, H. Yamashita, T. Ishio, S. Itoh, N. Shimomura, S. Anzai, H. Kawanishi, 3,000 ppi full-color "silicon display" with monolithic micro-LED and color conversion technology, : Proc. Int. Disp. Workshops (2021), https://doi.org/10.36463/idw.2020.0273.

[28] J. Shin, H. Kim, S. Sundaram, J. Jeong, B.-I. Park, C.S. Chang, J. Choi, T. Kim, M. Saravanapavanantham, K. Lu, S. Kim, J.M. Suh, K.S. Kim, M.-K. Song, Y. Liu, K. Qiao, J.H. Kim, Y. Kim, J.-H. Kang, J. Kim, D. Lee, J. Lee, J.S. Kim, H.E. Lee, H. Yeon, H.S. Kum, S.-H. Bae, V. Bulovic, K.J. Yu, K. Lee, K. Chung, Y.J. Hong, A. Ougazzaden, J. Kim, Vertical full-colour micro-LEDs via 2D materials-based layer transfer, Nature 614 (2023) 81–87, https://doi.org/10.1038/s41586-022-05612-1.

[29] H.X. Jiang, S.X. Jin, J. Li, J. Shakya, J.Y. Lin, III-nitride blue microdisplays, Appl. Phys. Lett. 78 (2001) 1303–1305, https://doi.org/10.1063/1.1351521.

[30] C. Griffin, H.X. Zhang, B. Guilhabert, D. Massoubre, E. Gu, M.D. Dawson, Micro-pixellated flip-chip InGaN and AlInGaN light-emitting diodes, : Opt. Info Conf. Pap. (2007).

[31] V. Poher, N. Grossman, G.T. Kennedy, K. Nikolic, H.X. Zhang, Z. Gong, E. M. Drakakis, E. Gu, M.D. Dawson, P.M.W. French, P. Degenaar, M.A.A. Neil, Micro-LED arrays: a tool for two-dimensional neuron stimulation, J. Phys. D. Appl. Phys. 41 (2008) 094014, https://doi.org/10.1088/0022-3727/41/9/094014.

[32] J. Day, J. Li, D.Y.C. Lie, C. Bradford, J.Y. Lin, H.X. Jiang, III-Nitride full-scale high-resolution microdisplays, Appl. Phys. Lett. 99 (2011), https://doi.org/10.1063/1.3615679.

[33] Zhao Jun Liu, Wing Cheung Chong, Ka Ming Wong, Kei May Lau, 360 PPI Flip-chip mounted active matrix addressable light emitting diode on silicon (LEDoS) micro-displays, J. Disp. Technol. 9 (2013) 678–682, https://doi.org/10.1109/JDT.2013.2256107.

[34] W.C. Chong, W.K. Cho, Z.J. Liu, C.H. Wang, K.M. Lau, 1700 Pixels per inch (PPI) passive-matrix micro-LED display powered by ASIC, in: 2014 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS), IEEE,, 2014, pp. 1–4, https://doi.org/10.1109/CSICS.2014.6978524.

[35] H.-V. Han, H.-Y. Lin, C.-C. Lin, W.-C. Chong, J.-R. Li, K.-J. Chen, P. Yu, T.-M. Chen, H.-M. Chen, K.-M. Lau, H.-C. Kuo, Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology, Opt. Express 23 (2015) 32504, https://doi.org/10.1364/OE.23.032504.

[36] H.-Y. Lin, C.-W. Sher, D.-H. Hsieh, X.-Y. Chen, H.-M.P. Chen, T.-M. Chen, K.-M. Lau, C.-H. Chen, C.-C. Lin, H.-C. Kuo, Optical cross-talk reduction in a quantum-dot-based full-color micro-light-emitting-diode display by a lithographic-fabricated photoresist mold, Photonics Res 5 (2017) 411, https://doi.org/10.1364/PRJ.5.000411.

[37] J. Bai, Y. Cai, P. Feng, P. Fletcher, X. Zhao, C. Zhu, T. Wang, A direct epitaxial approach to achieving ultrasmall and ultrabright InGaN micro light-emitting diodes (μLEDs), ACS Photonics 7 (2020) 411–415, https://doi.org/10.1021/acsphotonics.9b01351.

[38] M.S. Wong, J. Back, D. Hwang, C. Lee, J. Wang, S. Gandrothula, T. Margalith, J. S. Speck, S. Nakamura, S.P. Denbaars, Demonstration of high wall-plug efficiency III-nitride micro-light-emitting diodes with MOCVD-grown tunnel junction contacts using chemical treatments, Appl. Phys. Express 14 (2021), https://doi.org/10.35848/1882-0786/ac1230.

[39] M.Z. Baten, S. Alam, B. Sikder, A. Aziz, III-Nitride light-emitting devices, Photonics 8 (2021) 430, https://doi.org/10.3390/photonics8100430.

[40] K.A. Bulashevich, S.Y. Karpov, Impact of surface recombination on efficiency of III-nitride light-emitting diodes, Phys. Status Solidi - Rapid Res. Lett. 10 (2016), https://doi.org/10.1002/pssr.201600059.

[41] M.S. Wong, J.A. Kearns, C. Lee, J.M. Smith, C. Lynsky, G. Lheureux, H. Choi, J. Kim, C. Kim, S. Nakamura, J.S. Speck, S.P. DenBaars, Improved performance of AlGaInP red micro-light-emitting diodes with sidewall treatments, Opt. Express 28 (2020), https://doi.org/10.1364/oe.384127.

[42] T. Taki, M. Strassburg, Review—Visible LEDs: More than Efficient Light, ECS J. Solid State Sci. Technol. 9 (2020), https://doi.org/10.1149/2.0402001jss.

[43] K. Mudiyanselage, K. Katsiev, H. Idriss, Effects of experimental parameters on the growth of GaN nanowires on Ti-film/Si(1 0 0) and Ti-foil by molecular beam epitaxy, J. Cryst. Growth 547 (2020), https://doi.org/10.1016/j.jcrysgro.2020.125818.

[44] X. Jia, Y. Zhou, B. Liu, H. Lu, Z. Xie, R. Zhang, Y. Zheng, A simulation study on the enhancement of the efficiency of GaN-based blue light-emitting diodes at low current density for micro-LED applications, Mater. Res Express 6 (2019), https://doi.org/10.1088/2053-1591/ab3f7b.

[45] F. Chen, X. Ji, S.P. Lau, Recent progress in group III-nitride nanostructures: From materials to applications, Mater. Sci. Eng.: R: Rep. 142 (2020) 100578, https://doi.org/10.1016/j.mser.2020.100578.

[46] D. Hwang, A. Mughal, C.D. Pynn, S. Nakamura, S.P. DenBaars, Sustained high external quantum efficiency in ultrasmall blue III–nitride micro-LEDs, Appl. Phys. Express 10 (2017) 032101, https://doi.org/10.7567/APEX.10.032101.

[47] S. Mun, C. Kang, J. Min, S. Choi, W. Jeong, G. Kim, J. Lee, K. Kim, H.C. Ko, D. Lee, Highly efficient full-color inorganic LEDs on a single wafer by using multiple adhesive bonding, Adv. Mater. Interfaces 8 (2021), https://doi.org/10.1002/admi.202100300.

[48] M. Hetzl, F. Schuster, A. Winnerl, S. Weiszer, M. Stutzmann, GaN nanowires on diamond, Mater. Sci. Semicond. Process 48 (2016) 65–78, https://doi.org/10.1016/j.mssp.2016.03.013.

[49] A. Bengoechea-Encabo, F. Barbagini, S. Fernandez-Garrido, J. Grandal, J. Ristic, M.A. Sanchez-Garcia, E. Calleja, U. Jahn, E. Luna, A. Trampert, Understanding the selective area growth of GaN nanocolumns by MBE using Ti nanomasks, J. Cryst. Growth 325 (2011) 89–92, https://doi.org/10.1016/j.jcrysgro.2011.04.035.

[50] K. Kishino, H. Sekiguchi, A. Kikuchi, Improved Ti-mask selective-area growth (SAG) by rf-plasma-assisted molecular beam epitaxy demonstrating extremely uniform GaN nanocolumn arrays, J. Cryst. Growth 311 (2009) 2063–2068, https://doi.org/10.1016/j.jcrysgro.2008.11.056.

[51] M. Hetzl, F. Schuster, A. Winnerl, S. Weiszer, M. Stutzmann, GaN nanowires on diamond, Mater. Sci. Semicond. Process 48 (2016) 65–78, https://doi.org/10.1016/j.mssp.2016.03.013.

[52] F. Schuster, F. Furtmayr, R. Zamani, C. Magén, J.R. Morante, J. Arbiol, J. A. Garrido, M. Stutzmann, Self-Assembled GaN Nanowires on Diamond, Nano Lett. 12 (2012) 2199–2204, https://doi.org/10.1021/nl203872q.

[53] X. Zhang, M. Belloeil, P.-H. Jouneau, C. Bougerol, B. Gayral, B. Daudin, Chemical composition fluctuations and strain relaxation in InGaN nanowires: the role of the metal/nitrogen flux ratio, Mater. Sci. Semicond. Process 55 (2016) 79–84, https://doi.org/10.1016/j.mssp.2016.03.006.

[54] D. Tsivion, E. Joselevich, Guided growth of epitaxially coherent GaN nanowires on SiC, Nano Lett. 13 (2013), https://doi.org/10.1021/nl4030769.

[55] R. Mishra, A.K. Chhalodia, S.K. Tiwari, V. Mochalin, R. Bogdanowicz, V. Pichot, R. Bogdanowicz, H.-C. Chang, Q. Huang, A. Schell, M. Alkahtani, M. Alkahtani, Recent progress in nanodiamonds: synthesis, properties and their potential applications, Veruscript Funct. Nanomater. 2 (2018) 1–23, https://doi.org/10.22261/8W2EG0.

[56] R.K. Mishra, R. Rajakumari, Nanobiosensors for Biomedical Application, 2018. https://doi.org/10.1016/B978-0-12-814031-4.00001-5.

[57] R.K. Mishra, S.K. Tiwari, S. Mohapatra, S. Thomas, Efficient Nanocarriers for Drug-Delivery Systems. in: Nanocarriers for Drug Delivery, Elsevier, 2019, pp. 1–41, https://doi.org/10.1016/B978-0-12-814033-8.00001-1.

[58] S.V.S. Prasad, R.K. Mishra, S. Gupta, S.B. Prasad, S. Singh, Introduction, History, and Origin of Two Dimensional (2D) Materials, in: 2021: pp. 1–9. https://doi.org/10.1007/978-981-16-3322-5_1.

[59] S. Yaragalla, R. Mishra, S. Thomas, N. Kalarikkal, H.J. Maria, Carbon-Based Nanofillers their Rubber Nanocomp. (2018), https://doi.org/10.1016/C2016-0-03648-3.

[60] R.K. Mishra, A. Dutta, P. Mishra, S. Thomas, Recent Progress in Electromagnetic Absorbing Materials, : Adv. Mater. Electromagn. Shield. (2018), https://doi.org/10.1002/9781119128625.ch7.

[61] K.M. Raghvendra, Nanostructured biomimetic, bioresponsive, and bioactive biomaterials. in: Fundamental Biomaterials: Metals, Elsevier, 2018, pp. 35–65, https://doi.org/10.1016/B978-0-08-102205-4.00002-7.

[62] D. Tsivion, M. Schvartzman, R. Popovitz-Biro, P. von Huth, E. Joselevich, Guided growth of millimeter-long horizontal nanowires with controlled orientations, Science 333 (1979) (2011) 1003–1007, https://doi.org/10.1126/science.1208455.

[63] K. Kumar Mishra, Raghvendra, J. Cherusseri, Joseph, Thermal and crystallization behavior of micro and nano fibrillar in-situ composites, in: Micro and Nano Fibrillar Composites (MFCs and NFCs) from Polymer Blends, 1st ed., Woodhead Publishin,, 2017, pp. 213–231, https://doi.org/10.1016/B978-0-08-101991-7.00006-6.

[64] R.K. Mishra, S. Loganathan, S. Thomas, In-situ microfibrillar/nanofibrillar single polymer composites: Preparation, characterization, and application, 2017. https://doi.org/10.1016/B978-0-08-101991-7.00005-4.
[65] T.R. Kuykendall, M.V.P. Altoe, D.F. Ogletree, S. Aloni, Catalyst-directed crystallographic orientation control of GaN nanowire growth, Nano Lett. 14 (2014) 6767–6773, https://doi.org/10.1021/nl502079v.
[66] B. Alloing, J. Zúñiga-Pérez, Metalorganic chemical vapor deposition of GaN nanowires: From catalyst-assisted to catalyst-free growth, and from self-assembled to selective-area growth, Mater. Sci. Semicond. Process 55 (2016) 51–58, https://doi.org/10.1016/j.mssp.2016.03.025.
[67] S. Conesa-Boj, I. Zardo, S. Estradé, L. Wei, P. Jean Alet, P. Roca i Cabarrocas, J. R. Morante, F. Peiró, A.F. i Morral, J. Arbiol, Defect Formation in Ga-Catalyzed Silicon Nanowires, Cryst. Growth Des. 10 (2010) 1534–1543, https://doi.org/10.1021/cg900741y.
[68] H.X. Jiang, S.X. Jin, J. Li, J. Shakya, J.Y. Lin, III-nitride blue microdisplays, Appl. Phys. Lett. 78 (2001) 1303–1305, https://doi.org/10.1063/1.1351521.
[69] A. Pandey, Z. Mi, III-nitride nanostructures for high efficiency micro-LEDs and ultraviolet optoelectronics, IEEE J. Quantum Electron 58 (2022) 1–13, https://doi.org/10.1109/JQE.2022.3151965.
[70] J. Ryu, S. Park, Y. Park, S. Ryu, K. Hwang, H.W. Jang, Technological breakthroughs in chip fabrication, transfer, and color conversion for high-performance micro-LED displays, Adv. Mater. 35 (2023), https://doi.org/10.1002/adma.202204947.
[71] L.E. Brus, A simple model for the ionization potential, electron affinity, and aqueous redox potentials of small semiconductor crystallites, J. Chem. Phys. 79 (1983), https://doi.org/10.1063/1.445676.
[72] Y. Xia, P. Yang, Y. Sun, Y. Wu, B. Mayers, B. Gates, Y. Yin, F. Kim, H. Yan, One-dimensional nanostructures: synthesis, characterization, and applications, Adv. Mater. 15 (2003), https://doi.org/10.1002/adma.200390087.
[73] Y. Zhong, J. Zhang, S. Wu, L. Jia, X. Yang, Y. Liu, Y. Zhang, Q. Sun, A review on the GaN-on-Si power electronic devices, Fundam. Res. 2 (2022), https://doi.org/10.1016/j.fmre.2021.11.028.
[74] C.T. Ma, Z.H. Gu, Review on driving circuits for wide-bandgap semiconductor switching devices for mid-to high-power applications, Micro (Basel) 12 (2021), https://doi.org/10.3390/mi12010065.
[75] A. Abdullah, M.A. Kulkarni, H. Thaalbi, F. Tariq, S.W. Ryu, Epitaxial growth of 1D GaN-based heterostructures on various substrates for photonic and energy applications, Nanoscale Adv. 5 (2023), https://doi.org/10.1039/d2na00711h.
[76] T. Ueda, Gan power devices: Current status and future challenges, Jpn J. Appl. Phys. 58 (2019), https://doi.org/10.7567/1347-4065/ab12c9.
[77] T. Boles, GaN-on-Silicon - Present capabilities and future directions, in: AIP Conf Proc, 2018, https://doi.org/10.1063/1.5024484.
[78] H. Ishida, R. Kajitani, Y. Kinoshita, H. Umeda, S. Ujita, M. Ogawa, K. Tanaka, T. Morita, S. Tamura, M. Ishida, T. Ueda, GaN-based semiconductor devices for future power switching systems. in: Technical Digest - International Electron Devices Meeting, IEDM, 2017, https://doi.org/10.1109/IEDM.2016.7838460.
[79] M.A. Johar, H.-G. Song, A. Waseem, J.-H. Kang, J.-S. Ha, Y.-H. Cho, S.-W. Ryu, Ultrafast carrier dynamics of conformally grown semi-polar (11$\bar{2}$2) GaN/InGaN multiple quantum well co-axial nanowires on m-axial GaN core nanowires, Nanoscale 11 (2019) 10932–10943, https://doi.org/10.1039/C9NR02823D.
[80] M.A. Johar, A. Waseem, M.A. Hassan, I.V. Bagal, A. Abdullah, J.S. Ha, J.K. Lee, S. W. Ryu, Epitaxial growth of GaN core and InGaN/GaN multiple quantum well core/shell nanowires on a thermally conductive beryllium oxide substrate, ACS Omega 5 (2020), https://doi.org/10.1021/acsomega.0c02411.
[81] M.A. Johar, H.-G. Song, A. Waseem, J.-H. Kang, J.-S. Ha, Y.-H. Cho, S.-W. Ryu, Ultrafast carrier dynamics of conformally grown semi-polar (11$\bar{2}$2) GaN/InGaN multiple quantum well co-axial nanowires on m-axial GaN core nanowires, Nanoscale 11 (2019) 10932–10943, https://doi.org/10.1039/C9NR02823D.
[82] M.A. Johar, H.-G. Song, A. Waseem, M.A. Hassan, I.V. Bagal, Y.-H. Cho, S.-W. Ryu, Universal and scalable route to fabricate GaN nanowire-based LED on amorphous substrate by MOCVD, Appl. Mater. Today 19 (2020) 100541, https://doi.org/10.1016/j.apmt.2019.100541.
[83] A. Waseem, M.A. Johar, M.A. Hassan, I.V. Bagal, A. Abdullah, J.-S. Ha, J.K. Lee, S.-W. Ryu, Flexible self-powered piezoelectric pressure sensor based on GaN/p-GaN coaxial nanowires, J. Alloy. Compd. 872 (2021) 159661, https://doi.org/10.1016/j.jallcom.2021.159661.
[84] A. Abdullah, I.V. Bagal, A. Waseem, M.A. Kulkarni, H. Thaalbi, J.K. Lee, S.-W. Ryu, Engineering GaN nanowire photoanode interfaces for efficient and stable photoelectrochemical water splitting, Mater. Today Phys. 28 (2022) 100846, https://doi.org/10.1016/j.mtphys.2022.100846.
[85] K.M.A. Saron, M. Ibrahim, T.A. Taha, A.I. Aljameel, A.G. Alharbi, A.M. Alenad, B. A. Alshammari, G.N. Almutairi, N.K. Allam, Growth of high-quality GaN nanowires on p-Si (1 1 1) and their performance in solid state heterojunction solar cells, Sol. Energy 227 (2021) 525–531, https://doi.org/10.1016/j.solener.2021.09.045.
[86] D. Tsivion, E. Joselevich, Guided growth of horizontal GaN nanowires on spinel with orientation-controlled morphologies, J. Phys. Chem. C. 118 (2014), https://doi.org/10.1021/jp504785v.
[87] A. Rothman, V.G. Dubrovskii, E. Joselevich, Kinetics and mechanism of planar nanowire growth, Proc. Natl. Acad. Sci. USA 117 (2020), https://doi.org/10.1073/pnas.1911505116.
[88] A. Rothman, J. Maniš, V.G. Dubrovskii, T. Šikola, J. Mach, E. Joslevich, Kinetics of guided growth of horizontal gan nanowires on flat and faceted sapphire surfaces, Nanomaterials 11 (2021), https://doi.org/10.3390/nano11030624.
[89] Z. Liu, C.-H. Lin, B.-R. Hyun, C.-W. Sher, Z. Lv, B. Luo, F. Jiang, T. Wu, C.-H. Ho, H.-C. Kuo, J.-H. He, Micro-light-emitting diodes with quantum dots in display technology, Light Sci. Appl. 9 (2020) 83, https://doi.org/10.1038/s41377-020-0268-1.
[90] X. Li, D. Kundaliya, Z.J. Tan, M. Anc, N.X. Fang, Quantum Dots Color Converters for microLEDs: Material Composite and Patterning Technology. in: Conference on Lasers and Electro-Optics, Optica Publishing Group, Washington, D.C., 2020, p. STu3P.7, https://doi.org/10.1364/CLEO_SI.2020.STu3P.7.
[91] C.-T. Lee, C.-J. Cheng, H.-Y. Lee, Y.-C. Chu, Y.-H. Fang, C.-H. Chao, M.-H. Wu, Color conversion of GaN-based micro light-emitting diodes using quantum dots, IEEE Photonics Technol. Lett. 27 (2015) 2296–2299, https://doi.org/10.1109/LPT.2015.2462072.
[92] B.-R. Hyun, C.-W. Sher, Y.-W. Chang, Y. Lin, Z. Liu, H.-C. Kuo, Dual role of quantum dots as color conversion layer and suppression of input light for full-color micro-LED displays, J. Phys. Chem. Lett. 12 (2021) 6946–6954, https://doi.org/10.1021/acs.jpclett.1c00321.
[93] Y. Wu, Y. Xiao, I. Navid, K. Sun, Y. Malhotra, P. Wang, D. Wang, Y. Xu, A. Pandey, M. Reddeppa, W. Shin, J. Liu, J. Min, Z. Mi, InGaN micro-light-emitting diodes monolithically grown on Si: achieving ultra-stable operation through polarization and strain engineering, Light Sci. Appl. 11 (2022) 294, https://doi.org/10.1038/s41377-022-00985-4.
[94] Q. Liu, Z. Wang, L. Zhu, X. Cheng, J. Wang, Nano-grooves etching on top of GaN-LED for light extraction enhancement, Opt. Laser Technol. 138 (2021) 106842, https://doi.org/10.1016/j.optlastec.2020.106842.
[95] G. Lozano, S.R. Rodriguez, M.A. Verschuuren, J. Gómez Rivas, Metallic nanostructures for efficient LED lighting, Light Sci. Appl. 5 (2016) e16080, https://doi.org/10.1038/lsa.2016.80.
[96] S. Paul David, A. Soosaimanickam, T. Sakthivel, B. Sambandam, A. Sivaramalingam, Thin Film Metal Oxides for Displays and Other Optoelectronic Applications, in: 2021: pp. 185–250. https://doi.org/10.1007/978-3-030-53065-5_6.
[97] J.-H. Sung, J.S. Yang, B.-S. Kim, C.-H. Choi, M.-W. Lee, S.-G. Lee, S.-G. Park, E.-H. Lee, B.-H. O, Enhancement of electroluminescence in GaN-based light-emitting diodes by metallic nanoparticles, Appl. Phys. Lett. 96 (2010), https://doi.org/10.1063/1.3457349.
[98] S. Zhang, J. Zhang, J. Gao, X. Wang, C. Zheng, M. Zhang, X. Wu, L. Xu, J. Ding, Z. Quan, F. Jiang, Efficient emission of InGaN-based light-emitting diodes: toward orange and red, Photonics Res 8 (2020), https://doi.org/10.1364/prj.402555.
[99] J.H. Lee, A.B.M.H. Islam, T.K. Kim, Y.-J. Cha, J.S. Kwak, Impact of tin-oxide nanoparticles on improving the carrier transport in the Ag/p-GaN interface of InGaN/GaN micro-light-emitting diodes by originating inhomogeneous Schottky barrier height, Photonics Res 8 (2020) 1049, https://doi.org/10.1364/PRJ.385249.
[100] Y. Zhu, L. Li, C. Zhang, G. Casillas, Z. Sun, Z. Yan, G. Ruan, Z. Peng, A.-R.O. Raji, C. Kittrell, R.H. Hauge, J.M. Tour, A seamless three-dimensional carbon nanotube graphene hybrid material, Nat. Commun. 3 (2012) 1225, https://doi.org/10.1038/ncomms2234.
[101] I.C.S.G, H.Y.N. Raghvendra kumar mishra, Explor. Nexus Struct., Prop. Appl. Graph. Conduct., Biomater. Polym. Horiz. 1 (2022).
[102] A. Sosna-Głębska, N. Szczecińska, K. Znajdek, M. Sibiński, Review on metallic oxide nanoparticles and their application in optoelectronic devices, Acta Innov. (2019) 5–15, https://doi.org/10.32933/ActaInnovations.30.1.
[103] V.K. Yadu Nath, R.K. Mishra, M.S. Neelakandan, B. Aryat, P. Prasad, S. Thomas, Ultrafast characterization 2D semiconducting TMDC for nanoelectronics application, in: S.T.N.& S.K. Didier Rouxel (Ed.), Advanced Polymeric Materials: Synthesis and Applications, first ed., River Publishers, 2018, pp. 263–293.
[104] Y. Yan, Y. Xiao, J. Cai, Y. Zhang, Y. Ye, S. Xu, Q. Yan, T. Guo, E. Chen, Quantum-dot color wheel for projection displays, Optica 10 (2023) 1559, https://doi.org/10.1364/OPTICA.502938.
[105] V. Flauraud, M. Reyes, R. Paniagua-Domínguez, A.I. Kuznetsov, J. Brugger, Silicon nanostructures for bright field full color prints, ACS Photonics 4 (2017), https://doi.org/10.1021/acsphotonics.6b01021.
[106] I. Boyadzhiev, K. Bala, S. Paris, F. Durand, User-guided white balance for mixed lighting conditions, : ACM Trans. Graph (2012), https://doi.org/10.1145/2366145.2366219.
[107] H.S. Shim, M. Ko, S. Jeong, S.Y. Shin, S.M. Park, Y.R. Do, J.K. Song, Enhancement mechanism of quantum yield in alloyed-core/shell structure of ZnS-CuInS2/ZnS quantum dots, J. Phys. Chem. C. 125 (2021), https://doi.org/10.1021/acs.jpcc.0c10996.
[108] S. Lin, G. Tan, J. Yu, E. Chen, Y. Weng, X. Zhou, S. Xu, Y. Ye, Q.F. Yan, T. Guo, Multi-primary-color quantum-dot down-converting films for display applications, Opt. Express 27 (2019), https://doi.org/10.1364/oe.27.028480.
[109] Q. Yong, J. Chang, Q. Liu, F. Jiang, D. Wei, H. Li, Matt polyurethane coating: correlation of surface roughness on measurement length and gloss, Polymers 12 (2020), https://doi.org/10.3390/polym12020326.
[110] A. Agrawal, Y. Tchoe, Scaling study of molecular beam epitaxy grown InAs/Al2O3 films using atomic force microscopy, Thin Solid Films 709 (2020), https://doi.org/10.1016/j.tsf.2020.138204.
[111] M.F. Schubert, J.Q. Xi, J.K. Kim, E.F. Schubert, Distributed Bragg reflector consisting of high- and low-refractive-index thin film layers made of the same material, Appl. Phys. Lett. 90 (2007), https://doi.org/10.1063/1.2720269.
[112] P. Li, Y. Zhang, L. chen, Y. Yu, X. Han, L. Yan, G. Deng, B. Zhang, Optimization design and preparation of near ultraviolet AlGaN/GaN distributed Bragg reflectors, Superlattices Micro 122 (2018), https://doi.org/10.1016/j.spmi.2018.05.034.
[113] A. Yohso, K. Ukai, How color break-up occurs in the human-visual system: the mechanism of the color break-up phenomenon, J. Soc. Inf. Disp. 14 (2006), https://doi.org/10.1889/1.2408396.

[114] Y.C. Shih, F.G. Shi, Quantum dot based enhancement or elimination of color filters for liquid crystal display, IEEE J. Sel. Top. Quantum Electron. 23 (2017), https://doi.org/10.1109/JSTQE.2017.2748923.

[115] J.H. Kwon, H.J. Jun, J.S. Gwag, H.S. Lee, Effect of wavelength-dependent scattering on the color chromaticity of the LCD backlight, J. Opt. Soc. Korea 17 (2013), https://doi.org/10.3807/JOSK.2013.17.3.275.

[116] W. Zhang, Y. Chen, J. Cai, L. Deng, S. Xu, Y. Ye, Q. Yan, T. Guo, E. Chen, Uniformity improvement of a mini-LED backlight by a quantum-dot color conversion film with nonuniform thickness, Opt. Lett. 48 (2023) 5643, https://doi.org/10.1364/OL.505552.

[117] S. Raghvendra, kumar Mishra, Abraham Jiji, Kalarikkal, Nandakumar, Jayanarayanan, Karingamanna, Joseph, Kuruvilla, Thomas, Conducting Polyurethane Composites. in: Polyurethane Polymers: Composites and Nanocomposites, 1st ed, Elsevier, 2017, pp. 365–399, https://doi.org/10.1016/B978-0-12-804065-2.00012-7.

[118] Raghvendra Kumar Mishra, Graphene-based fibers and their application in advanced composites system, in: D.B.H.S.A.K.H.Omari V. Mukbaniani (Ed.), In Composite Materials for Industry, Electronics, and the Environment, 1st ed., Apple Academic Press,, USA, 2019, pp. 3–23.

[119] S.L.J.J.P.S.S.T. Raghvendra Kumar Mishra, Progress in polymer nanocomposites for electromagnetic shielding application, in: E.B.M.J.S.T.P.K.M. Reza, K. Haghi (Eds.), Modern Physical Chemistry: Engineering Models, Materials, and Methods with Applications, 1st ed., Apple Academic Press, New York, 2018, pp. 198–237.

[120] L. Zhang, F. Ou, W.C. Chong, Y. Chen, Y. Zhu, Q. Li, 59-3: *Distinguished Paper:* wafer scale hybrid monolithic integration of Si-based IC and III-V Epilayers - a mass manufacturable approach for active matrix micro-LED displays, SID Symp. . Dig. Tech. Pap. 49 (2018) 786–789, https://doi.org/10.1002/sdtp.12374.

[121] Y. Fu, J. Sun, Z. Du, W. Guo, C. Yan, F. Xiong, L. Wang, Y. Dong, C. Xu, J. Deng, T. Guo, Q. Yan, Monolithic integrated device of GaN Micro-LED with graphene transparent electrode and graphene active-matrix driving transistor, Materials 12 (2019) 428, https://doi.org/10.3390/ma12030428.

[122] D. Chen, Y.-C. Chen, G. Zeng, D.W. Zhang, H.-L. Lu, Integration technology of Micro-LED for next-generation display, Research 6 (2023), https://doi.org/10.34133/research.0047.

[123] C. Jung Hun, S.J. Lee, K.O. Kwon, J.Y. Choi, T. Jung, M. Han, S.J. Han, A monolithically integrated micro-LED display based on GaN-on-silicon substrate, Appl. Phys. Express 13 (2020) 026501, https://doi.org/10.7567/1882-0786/ab64ff.

[124] P. Tian, J.J.D. McKendry, Z. Gong, B. Guilhabert, I.M. Watson, E. Gu, Z. Chen, G. Zhang, M.D. Dawson, Size-dependent efficiency and efficiency droop of blue InGaN micro-light emitting diodes, Appl. Phys. Lett. 101 (2012), https://doi.org/10.1063/1.4769835.

[125] J.M. Smith, R. Ley, M.S. Wong, Y.H. Baek, J.H. Kang, C.H. Kim, M.J. Gordon, S. Nakamura, J.S. Speck, S.P. Denbaars, Comparison of size-dependent characteristics of blue and green InGaN microLEDs down to 1 μ m in diameter, Appl. Phys. Lett. 116 (2020), https://doi.org/10.1063/1.5144819.

[126] J.M. Lee, C. Huh, D.J. Kim, S.J. Park, Dry-etch damage and its recovery in InGaN/GaN multi-quantum-well light-emitting diodes, Semicond. Sci. Technol. 18 (2003), https://doi.org/10.1088/0268-1242/18/6/323.

[127] R.T. Ley, J.M. Smith, M.S. Wong, T. Margalith, S. Nakamura, S.P. Denbaars, M. J. Gordon, Revealing the importance of light extraction efficiency in InGaN/GaN microLEDs via chemical treatment and dielectric passivation, Appl. Phys. Lett. 116 (2020), https://doi.org/10.1063/5.0011651.

[128] D.M. Geum, S.K. Kim, C.M. Kang, S.H. Moon, J. Kyhm, J. Han, D.S. Lee, S. Kim, Strategy toward the fabrication of ultrahigh-resolution micro-LED displays by bonding-interface-engineered vertical stacking and surface passivation, Nanoscale 11 (2019), https://doi.org/10.1039/c9nr04423j.

[129] Y. Yang, X.A. Cao, Removing plasma-induced sidewall damage in GaN-based light-emitting diodes by annealing and wet chemical treatments, J. Vac. Sci. Technol. B: Microelectron. Nanometer Struct. Process., Meas., Phenom. 27 (2009), https://doi.org/10.1116/1.3244590.

[130] M. Hartensveld, G. Ouin, C. Liu, J. Zhang, Effect of KOH passivation for top-down fabricated InGaN nanowire light emitting diodes, J. Appl. Phys. 126 (2019), https://doi.org/10.1063/1.5123171.

[131] P. Kirilenko, D. Iida, Z. Zhuang, K. Ohkawa, InGaN-based green micro-LED efficiency enhancement by hydrogen passivation of the p-GaN sidewall, Appl. Phys. Express 15 (2022), https://doi.org/10.35848/1882-0786/ac7fdc.

[132] S. Keller, S.S. Pasayat, C. Gupta, S.P. DenBaars, S. Nakamura, U.K. Mishra, Patterned III-nitrides on porous gan: extending elastic relaxation from the nano- to the micrometer scale, Phys. Status Solidi - Rapid Res. Lett. 15 (2021), https://doi.org/10.1002/pssr.202100234.

[133] S. Alam, S. Sundaram, X. Li, Y. El Gmili, M. Elouneg-Jamroz, I.C. Robin, G. Patriarche, J.P. Salvestrini, P.L. Voss, A. Ougazzaden, Emission wavelength red-shift by using "semi-bulk" InGaN buffer layer in InGaN/InGaN multiple-quantum-well, Superlattices Micro 112 (2017), https://doi.org/10.1016/j.spmi.2017.09.032.

[134] S. Zhou, X. Liu, H. Yan, Y. Gao, H. Xu, J. Zhao, Z. Quan, C. Gui, S. Liu, The effect of nanometre-scale V-pits on electronic and optical properties and efficiency droop of GaN-based green light-emitting diodes, Sci. Rep. 8 (2018), https://doi.org/10.1038/s41598-018-29440-4.

[135] Z. Chen, S. Yan, C. Danesh, MicroLED technologies and applications: characteristics, fabrication, progress, and challenges, J. Phys. D. Appl. Phys. 54 (2021), https://doi.org/10.1088/1361-6463/abcfe4.

[136] X. Zhou, P. Tian, C.-W. Sher, J. Wu, H. Liu, R. Liu, H.-C. Kuo, Growth, transfer printing and colour conversion techniques towards full-colour micro-LED display, Prog. Quantum Electron 71 (2020) 100263, https://doi.org/10.1016/j.pquantelec.2020.100263.

[137] S. Zhang, H. Zheng, L. Zhou, H. Li, Y. Chen, C. Wei, T. Wu, W. Lv, G. Zhang, S. Zhang, Z. Gong, B. Jia, H. Lin, Z. Gao, W. Xu, H. Ning, Research progress of micro-LED display technology, Crystals 13 (2023) 1001, https://doi.org/10.3390/cryst13071001.

[138] A. Carlson, A.M. Bowen, Y. Huang, R.G. Nuzzo, J.A. Rogers, Transfer printing techniques for materials assembly and micro/nanodevice fabrication, Adv. Mater. 24 (2012) 5284–5318, https://doi.org/10.1002/adma.201201386.

[139] J. Yu, T. Tao, B. Liu, F. Xu, Y. Zheng, X. Wang, Y. Sang, Y. Yan, Z. Xie, S. Liang, D. Chen, P. Chen, X. Xiu, Y. Zheng, R. Zhang, Investigations of sidewall passivation technology on the optical performance for smaller Size GaN-based micro-LEDs, Crystals 11 (2021) 403, https://doi.org/10.3390/cryst11040403.

[140] R. Voelkel, U. Vogler, A. Bramati, A. Erdmann, N. Ünal, U. Hofmann, M. Hennemeyer, R. Zoberbier, D. Nguyen, J. Brugger, Lithographic process window optimization for mask aligner proximity lithography, in: K. Lai, A. Erdmann (Eds.), 2014: p. 90520G. https://doi.org/10.1117/12.2046332.

[141] C. Kathe, F. Michoud, P. Schönle, A. Rowald, N. Brun, J. Ravier, I. Furfaro, V. Paggi, K. Kim, S. Soloukey, L. Asboth, T.H. Hutson, I. Jelescu, A. Philippides, N. Alwahab, J. Gandar, D. Huber, C.I. De Zeeuw, Q. Barraud, Q. Huang, S. P. Lacour, G. Courtine, Wireless closed-loop optogenetics across the entire dorsoventral spinal cord in mice, Nat. Biotechnol. 40 (2022) 198–208, https://doi.org/10.1038/s41587-021-01019-x.

[142] L. Zhang, F. Ou, W.C. Chong, Y. Chen, Q. Li, Wafer-scale monolithic hybrid integration of <scp>Si</scp> -based <scp>IC</scp> and <scp>III–V</scp> epi-layers—a mass manufacturable approach for active matrix micro-<scp>LED</scp> micro-displays, J. Soc. Inf. Disp. 26 (2018) 137–145, https://doi.org/10.1002/jsid.649.

[143] C. Jürgenhake, T. Falkowski, C. Fechtelpeter, R. Dumitrescu, Function-based feasibility study and benchmark for MID concepts, Procedia Technol. 26 (2016) 324–332, https://doi.org/10.1016/j.protcy.2016.08.042.

[144] D. Moser, J. Krause, 3D-MID — Multifunctional Packages for Sensors in Automotive Applications, in: Advanced Microsystems for Automotive Applications 2006, Springer-Verlag, Berlin/Heidelberg, n.d.: pp. 369–375. https://doi.org/10.1007/3-540-33410-6_27.

[145] M. Ankenbrand, M. Scheetz, J. Franke, K. Lomakin, M. Sippel, G. Gold, K. Helmreich, Generation of 3D functional structures for high- frequency applications by printing technologies, in: 2018 13th International Congress Molded Interconnect Devices (MID), IEEE,, 2018, pp. 1–5, https://doi.org/10.1109/ICMID.2018.8527052.

[146] P. Li, A. David, H. Li, H. Zhang, C. Lynsky, Y. Yang, M. Iza, J.S. Speck, S. Nakamura, S.P. Denbaars, High-temperature electroluminescence properties of InGaN red 40 × 40 μ m2micro-light-emitting diodes with a peak external quantum efficiency of 3.2%, Appl. Phys. Lett. 119 (2021) https://doi.org/10.1063/5.0070275.

[147] R.H. Horng, C.X. Ye, P.W. Chen, D. Iida, K. Ohkawa, Y.R. Wu, D.S. Wuu, Study on the effect of size on InGaN red micro-LEDs, Sci. Rep. 12 (2022), https://doi.org/10.1038/s41598-022-05370-0.

[148] S. Zhang, H. Zheng, L. Zhou, H. Li, Y. Chen, C. Wei, T. Wu, W. Lv, G. Zhang, S. Zhang, Z. Gong, B. Jia, H. Lin, Z. Gao, W. Xu, H. Ning, Research Progress of Micro-LED Display Technology, Crystals 13 (2023) 1001, https://doi.org/10.3390/cryst13071001.

[149] M.D. Dawson, Gallium nitride micro-LED displays (Conference Presentation), in: H. Morkoç, H. Fujioka, U.T. Schwarz (Eds.), Gallium Nitride Materials and Devices XIV, SPIE,, 2019, p. 58, https://doi.org/10.1117/12.2503586.

[150] M. Rajan Philip, D.D. Choudhary, M. Djavid, M.N. Bhuyian, T.H.Q. Bui, D. Misra, A. Khreishah, J. Piao, H.D. Nguyen, K.Q. Le, H.P.T. Nguyen, Fabrication of phosphor-free III-nitride nanowire light-emitting diodes on metal substrates for flexible photonics, ACS Omega 2 (2017) 5708–5714, https://doi.org/10.1021/acsomega.7b00843.

[151] Z. Pan, C. Guo, Z. Gong, 18.3: Tape-assisted laser transfer techniques for selective transfer of Micro-LEDs with high placement accuracy, SID Symp. . Dig. Tech. Pap. 52 (2021) 242–243, https://doi.org/10.1002/sdtp.15080.

[152] Z. Liu, K. Ren, G. Dai, J. Zhang, A review on micro-LED display integrating metasurface structures, Micro 14 (2023) 1354, https://doi.org/10.3390/mi14071354.

[153] O. Ambacher, Growth and applications of Group III-nitrides, J. Phys. D. Appl. Phys. 31 (1998) 2653–2710, https://doi.org/10.1088/0022-3727/31/20/001.

[154] Z. Lei, S. Xu, J. Wan, P. Wu, Facile preparation and multifunctional applications of boron nitride quantum dots, Nanoscale 7 (2015) 18902–18907, https://doi.org/10.1039/C5NR05960G.

[155] T. Leneke, S. Hirsch, B. Schmidt, A Multilayer process for the connection of fine-pitch-devices on molded interconnect devices (MIDs). in: Volume 13: Nano-Manufacturing Technology; and Micro and Nano Systems, Parts A and B, ASMEDC, 2008, pp. 305–312, https://doi.org/10.1115/IMECE2008-68620.

[156] J. Herrnsdorf, J.J.D. McKendry, Shuailong Zhang, Enyuan Xie, R. Ferreira, D. Massoubre, A.M. Zuhdi, R.K. Henderson, I. Underwood, S. Watson, A.E. Kelly, E. Gu, M.D. Dawson, Active-matrix GaN micro light-emitting diode display with unprecedented brightness, IEEE Trans. Electron Devices 62 (2015) 1918–1925, https://doi.org/10.1109/TED.2015.2416915.

[157] A.R. Anwar, M.T. Sajjad, M.A. Johar, C.A. Hernández-Gutiérrez, M. Usman, S. P. Łepkowski, Recent progress in micro-LED-based display technologies, Laser Photon Rev. 16 (2022), https://doi.org/10.1002/lpor.202100427.

[158] Y. Wu, J. Ma, P. Su, L. Zhang, B. Xia, Full-color realization of micro-LED displays, Nanomaterials 10 (2020) 2482, https://doi.org/10.3390/nano10122482.

[159] P. Li, H. Li, Y. Yao, H. Zhang, C. Lynsky, K.S. Qwah, J.S. Speck, S. Nakamura, S. P. DenBaars, Demonstration of high efficiency cascaded blue and green micro-light-emitting diodes with independent junction control, Appl. Phys. Lett. 118 (2021), https://doi.org/10.1063/5.0054005.
[160] A. David, Surface-roughened light-emitting diodes: an accurate model, J. Disp. Technol. 9 (2013) 301–316, https://doi.org/10.1109/JDT.2013.2240373.
[161] D. Kim, K.M. Song, U.J. Jung, S. Kim, D.S. Shin, J. Park, Effects of different InGaN/GaN electron emission layers/interlayers on performance of a UV-A LED, Appl. Sci. (Switz.) 10 (2020), https://doi.org/10.3390/app10041514.
[162] D. Schiavon, R. Mroczyński, A. Kafar, G. Kamler, I. Levchenko, S. Najda, P. Perlin, Refractive index of heavily germanium-doped gallium nitride measured by spectral reflectometry and ellipsometry, Materials 14 (2021), https://doi.org/10.3390/ma14237364.
[163] J.W. Orton, C.T. Foxon, Group III nitride semiconductors for short wavelength light-emitting devices, Rep. Prog. Phys. 61 (1998) 1–75, https://doi.org/10.1088/0034-4885/61/1/001.
[164] M.R. Krames, M. Ochiai-Holcomb, G.E. Höfler, C. Carter-Coman, E.I. Chen, I.-H. Tan, P. Grillot, N.F. Gardner, H.C. Chui, J.-W. Huang, S.A. Stockman, F.A. Kish, M.G. Craford, T.S. Tan, C.P. Kocot, M. Hueschen, J. Posselt, B. Loh, G. Sasser, D. Collins, High-power truncated-inverted-pyramid (AlxGa1−x)0.5In0.5P/GaP light-emitting diodes exhibiting >50% external quantum efficiency, Appl. Phys. Lett. 75 (1999) 2365–2367, https://doi.org/10.1063/1.125016.
[165] D. Feezell, S. Nakamura, Invention, development, and status of the blue light-emitting diode, the enabler of solid-state lighting, C. R. Phys. 19 (2018) 113–133, https://doi.org/10.1016/j.crhy.2017.12.001.
[166] J.Y. Lin, H.X. Jiang, IIInitride ultraviolet micro- and nano-photonics, in: in: (CLEO). Conference on Lasers and Electro-Optics, 2005., Vol. 2, IEEE, 2005, pp. 1441–1443, https://doi.org/10.1109/CLEO.2005.202152.
[167] C. Zhou, A. Ghods, V.G. Saravade, P.V. Patel, K.L. Yunghans, C. Ferguson, Y. Feng, B. Kucukgok, N. Lu, I.T. Ferguson, Review—the current and emerging applications of the III-nitrides, ECS J. Solid State Sci. Technol. 6 (2017) Q149–Q156, https://doi.org/10.1149/2.0101712jss.
[168] X. Liu, Y. Sun, Y. Malhotra, A. Pandey, Y. Wu, K. Sun, Z. Mi, High efficiency InGaN nanowire tunnel junction green micro-LEDs, Appl. Phys. Lett. 119 (2021), https://doi.org/10.1063/5.0059701.
[169] J.P. Kozak, R. Zhang, M. Porter, Q. Song, J. Liu, B. Wang, R. Wang, W. Saito, Y. Zhang, Stability, reliability, and robustness of GaN power devices: a review, IEEE Trans. Power Electron 38 (2023), https://doi.org/10.1109/TPEL.2023.3266365.
[170] M.R. Philip, D.D. Choudhary, M. Djavid, K.Q. Le, J. Piao, H.P.T. Nguyen, High efficiency green/yellow and red InGaN/AlGaN nanowire light-emitting diodes grown by molecular beam epitaxy, J. Sci.: Adv. Mater. Devices 2 (2017), https://doi.org/10.1016/j.jsamd.2017.05.009.
[171] R. Wang, H.P.T. Nguyen, A.T. Connie, J. Lee, I. Shih, Z. Mi, Color-tunable, phosphor-free InGaN nanowire light-emitting diode arrays monolithically integrated on silicon, Opt. Express 22 (2014), https://doi.org/10.1364/oe.22.0a1768.
[172] F. Akyol, D.N. Nath, S. Krishnamoorthy, P.S. Park, S. Rajan, Suppression of electron overflow and efficiency droop in N-polar GaN green light emitting diodes, Appl. Phys. Lett. 100 (2012), https://doi.org/10.1063/1.3694967.
[173] S.H. Yen, Y.K. Kuo, Polarization-dependent optical characteristics of violet InGaN laser diodes, J. Appl. Phys. 103 (2008), https://doi.org/10.1063/1.2937247.
[174] T. Kehagias, G.P. Dimitrakopulos, P. Becker, J. Kioseoglou, F. Furtmayr, T. Koukoula, I. Häusler, A. Chernikov, S. Chatterjee, T. Karakostas, H.M. Solowan, U.T. Schwarz, M. Eickhoff, P. Komninou, Nanostructure and strain in InGaN/GaN superlattices grown in GaN nanowires, Nanotechnology 24 (2013), https://doi.org/10.1088/0957-4484/24/43/435702.
[175] B. Park, J.K. Lee, C.T. Koch, M. Wölz, L. Geelhaar, S.H. Oh, High-resolution mapping of strain partitioning and relaxation in InGaN/GaN nanowire heterostructures, Adv. Sci. 9 (2022), https://doi.org/10.1002/advs.202200323.
[176] Y. Hou, F. Liang, D. Zhao, Z. Liu, P. Chen, J. Yang, Improvement of interface morphology and luminescence properties of InGaN/GaN multiple quantum wells by thermal annealing treatment, Results Phys. 31 (2021), https://doi.org/10.1016/j.rinp.2021.105057.
[177] N.A.K. Kaufmann, A. Dussaigne, D. Martin, P. Valvin, T. Guillet, B. Gil, F. Ivaldi, S. Kret, N. Grandjean, Thermal annealing of molecular beam epitaxy-grown InGaN/GaN single quantum well, Semicond. Sci. Technol. 27 (2012), https://doi.org/10.1088/0268-1242/27/10/105023.
[178] W.V. Lundin, A.E. Nikolaev, A.V. Sakharov, E.E. Zavarin, G.A. Valkovskiy, M. A. Yagovkina, S.O. Usov, N.V. Kryzhanovskaya, V.S. Sizov, P.N. Brunkov, A. L. Zakgeim, A.E. Cherniakov, N.A. Cherkashin, M.J. Hytch, E.V. Yakovlev, D. S. Bazarevskiy, M.M. Rozhavskaya, A.F. Tsatsulnikov, Single quantum well deep-green LEDs with buried InGaN/GaN short-period superlattice, J. Cryst. Growth 315 (2011), https://doi.org/10.1016/j.jcrysgro.2010.09.043.
[179] S.J. Leem, Y.C. Shin, K.C. Kim, E.H. Kim, Y.M. Sung, Y. Moon, S.M. Hwang, T. G. Kim, The effect of the low-mole InGaN structure and InGaN/GaN strained layer superlattices on optical performance of multiple quantum well active layers, J. Cryst. Growth 311 (2008), https://doi.org/10.1016/j.jcrysgro.2008.10.047.
[180] Y.H. Ra, R.T. Rashid, X. Liu, J. Lee, Z. Mi, Scalable nanowire photonic crystals: molding the light emission of InGaN, Adv. Funct. Mater. 27 (2017), https://doi.org/10.1002/adfm.201702364.
[181] Y.H. Ra, R.T. Rashid, X. Liu, S.M. Sadaf, K. Mashooq, Z. Mi, An electrically pumped surface-emitting semiconductor green laser, Sci. Adv. 6 (2020), https://doi.org/10.1126/sciadv.aav7523.
[182] R. Merlin, S.M. Young, Photonic crystals as topological high-Q resonators, Opt. Express 22 (2014), https://doi.org/10.1364/oe.22.018579.
[183] X. Liu, Y. Wu, Y. Malhotra, Y. Sun, Z. Mi, Micrometer scale InGaN green light emitting diodes with ultra-stable operation, Appl. Phys. Lett. 117 (2020), https://doi.org/10.1063/5.0005436.
[184] H.X. Jiang, J.Y. Lin, Nitride micro-LEDs and beyond - a decade progress review, Opt. Express 21 (2013) A475, https://doi.org/10.1364/OE.21.00A475.
[185] D. Starikov, C. Boney, I. Berishev, I.C. Hernandez, A. Bensaoula, Radio-frequency molecular-beam-epitaxy growth of III nitrides for microsensor applications, J. Vac. Sci. Technol. B: Microelectron. Nanometer Struct. Process., Meas., Phenom. 19 (2001) 1404–1408, https://doi.org/10.1116/1.1386382.
[186] A. Pandey, Z. Mi, III-nitride nanostructures for high efficiency micro-LEDs and ultraviolet optoelectronics, IEEE J. Quantum Electron 58 (2022) 1–13, https://doi.org/10.1109/JQE.2022.3151965.
[187] A. Ben Slimane, III-Nitride micro and nano structures for solid state lightning, KAUST Res. Repos. (2014).
[188] J.J. Wierer, N. Tansu, III-Nitride micro-LEDs for efficient emissive displays, Laser Photon Rev. 13 (2019), https://doi.org/10.1002/lpor.201900141.
[189] A. Ben Slimane, III-Nitride micro and nano structures for solid state lightning, KAUST Res. Repos. (2014).
[190] F. Chen, X. Ji, S.P. Lau, Recent progress in group III-nitride nanostructures: from materials to applications, Mater. Sci. Eng.: R: Rep. 142 (2020) 100578, https://doi.org/10.1016/j.mser.2020.100578.
[191] K.E. Waldrip, J. Han, J.J. Figiel, H. Zhou, E. Makarona, A.V. Nurmikko, Stress engineering during metalorganic chemical vapor deposition of AlGaN/GaN distributed Bragg reflectors, Appl. Phys. Lett. 78 (2001), https://doi.org/10.1063/1.1371240.
[192] G. Cosendey, A. Castiglia, G. Rossbach, J.F. Carlin, N. Grandjean, Blue monolithic AlInN-based vertical cavity surface emitting laser diode on free-standing GaN substrate, Appl. Phys. Lett. 101 (2012), https://doi.org/10.1063/1.4757873.
[193] T. Hamaguchi, N. Fuutagawa, S. Izumi, M. Murayama, H. Narui, Milliwatt-class GaN-based blue vertical-cavity surface-emitting lasers fabricated by epitaxial lateral overgrowth, Phys. Status Solidi (A) Appl. Mater. Sci. 213 (2016), https://doi.org/10.1002/pssa.201532759.
[194] S.P. DenBaars, D. Feezell, K. Kelchner, S. Pimputkar, C.-C. Pan, C.-C. Yen, S. Tanaka, Y. Zhao, N. Pfaff, R. Farrell, M. Iza, S. Keller, U. Mishra, J.S. Speck, S. Nakamura, Development of gallium-nitride-based light-emitting diodes (LEDs) and laser diodes for energy-efficient lighting and displays, Acta Mater. 61 (2013) 945–951, https://doi.org/10.1016/j.actamat.2012.10.042.
[195] M.-H. Sheen, Y.-H. Lee, J. Jang, J. Baek, O. Nam, C.-W. Yang, Y.-W. Kim, Correlation between the surface undulation and luminescence characteristics in semi-polar 112¯2 InGaN/GaN multi-quantum wells, Nanomaterials 13 (2023) 1946, https://doi.org/10.3390/nano13131946.
[196] H.P. Maruska, J.J. Tietjen, The preparation and properties of vapor-deposited single-crystal-line GaN, Appl. Phys. Lett. 15 (1969) 327–329, https://doi.org/10.1063/1.1652845.
[197] A. Pandey, Z. Mi, III-Nitride nanostructures for high efficiency micro-LEDs and ultraviolet optoelectronics, IEEE J. Quantum Electron 58 (2022) 1–13, https://doi.org/10.1109/JQE.2022.3151965.
[198] H.-V. Han, H.-Y. Lin, C.-C. Lin, W.-C. Chong, J.-R. Li, K.-J. Chen, P. Yu, T.-M. Chen, H.-M. Chen, K.-M. Lau, H.-C. Kuo, Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology, Opt. Express 23 (2015) 32504, https://doi.org/10.1364/OE.23.032504.
[199] S. Zhang, H. Zheng, L. Zhou, H. Li, Y. Chen, C. Wei, T. Wu, W. Lv, G. Zhang, S. Zhang, Z. Gong, B. Jia, H. Lin, Z. Gao, W. Xu, H. Ning, Research Progress of Micro-LED Display Technology, Crystals 13 (2023) 1001, https://doi.org/10.3390/cryst13071001.
[200] H.-V. Han, H.-Y. Lin, C.-C. Lin, W.-C. Chong, J.-R. Li, K.-J. Chen, P. Yu, T.-M. Chen, H.-M. Chen, K.-M. Lau, H.-C. Kuo, Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology, Opt. Express 23 (2015) 32504, https://doi.org/10.1364/OE.23.032504.
[201] W.C. Chong, K.M. Wong, Z.J. Liu, K.M. Lau, 60.4: A Novel Full-Color 3LED Projection System using R-G-B Light Emitting Diodes on Silicon (LEDoS) Micro-displays, SID Symp. . Dig. Tech. Pap. 44 (2013) 838–841, https://doi.org/10.1002/j.2168-0159.2013.tb06348.x.
[202] Y.J. Hong, C. Lee, A. Yoon, M. Kim, H. Seong, H.J. Chung, C. Sone, Y.J. Park, G. Yi, Visible-color-tunable light-emitting diodes, Adv. Mater. 23 (2011) 3284–3288, https://doi.org/10.1002/adma.201100806.
[203] Y.-M. Huang, K.J. Singh, A.-C. Liu, C.-C. Lin, Z. Chen, K. Wang, Y. Lin, Z. Liu, T. Wu, H.-C. Kuo, Advances in quantum-dot-based displays, Nanomaterials 10 (2020) 1327, https://doi.org/10.3390/nano10071327.
[204] Y. Huang, E.-L. Hsiang, M.-Y. Deng, S.-T. Wu, Mini-LED, Micro-LED and OLED displays: present status and future perspectives, Light Sci. Appl. 9 (2020) 105, https://doi.org/10.1038/s41377-020-0341-9.
[205] P. Tian, X. Shan, S. Zhu, E. Xie, J.J.D. McKendry, E. Gu, M.D. Dawson, AlGaN ultraviolet micro-LEDs, IEEE J. Quantum Electron 58 (2022), https://doi.org/10.1109/JQE.2022.3159854.
[206] T. Wu, C.-W. Sher, Y. Lin, C.-F. Lee, S. Liang, Y. Lu, S.-W. Huang Chen, W. Guo, H.-C. Kuo, Z. Chen, Mini-LED and Micro-LED: promising candidates for the next generation display technology, Appl. Sci. 8 (2018) 1557, https://doi.org/10.3390/app8091557.
[207] K. Khanafer, K. Vafai, Applications of Nanomaterials in Solar Energy and Desalination Sectors, in: 2013: pp. 303–329. https://doi.org/10.1016/B978-0-12-407819-2.00005-0.
[208] H.Q.T. Bui, R.T. Velpula, B. Jain, O.H. Aref, H.-D. Nguyen, T.R. Lenka, H.P. T. Nguyen, Full-color InGaN/AlGaN nanowire micro light-emitting diodes grown by molecular beam epitaxy: a promising candidate for next generation micro displays, Micro 10 (2019) 492, https://doi.org/10.3390/mi10080492.

[209] M. Beeler, E. Trichas, E. Monroy, III-nitride semiconductors for intersubband optoelectronics: A review, Semicond. Sci. Technol. 28 (2013), https://doi.org/10.1088/0268-1242/28/7/074022.

[210] B.R. Tull, N. Twu, Y.-J. Hsu, S. Leblebici, I. Kymissis, V.W. Lee, 19-1: *Invited Paper*: Micro-LED Microdisplays by Integration of III-V LEDs with Silicon Thin Film Transistors, SID Symp. . Dig. Tech. Pap. 48 (2017) 246–248, https://doi.org/10.1002/sdtp.11680.

[211] Y. Fu, J. Sun, Z. Du, W. Guo, C. Yan, F. Xiong, L. Wang, Y. Dong, C. Xu, J. Deng, T. Guo, Q. Yan, Monolithic integrated device of GaN micro-LED with graphene transparent electrode and graphene active-matrix driving transistor, Materials 12 (2019) 428, https://doi.org/10.3390/ma12030428.

[212] M.D. Dawson, J. Herrnsdorf, E. Xie, E. Gu, J. McKendry, A.D. Griffiths, M. J. Strain, 44-1: *Invited Paper:* Micro-LEDs for technological convergence between displays, optical communications, and sensing and imaging systems, SID Symp. . Dig. Tech. Pap. 51 (2020) 638–641, https://doi.org/10.1002/sdtp.13948.

[213] D.-S. Lee, J.-H. Han, Micro-LED Technology for Display Applications, in: 2021: pp. 271–305. https://doi.org/10.1007/978-981-33-6582-7_12.

[214] J. Osinski, P. Palomaki, Quantum dot design criteria for color conversion in microLED displays, : Dig. Tech. Pap. (2019), https://doi.org/10.1002/sdtp.12849.

[215] S.P. DenBaars, D. Feezell, K. Kelchner, S. Pimputkar, C.-C. Pan, C.-C. Yen, S. Tanaka, Y. Zhao, N. Pfaff, R. Farrell, M. Iza, S. Keller, U. Mishra, J.S. Speck, S. Nakamura, Development of gallium-nitride-based light-emitting diodes (LEDs) and laser diodes for energy-efficient lighting and displays, Acta Mater. 61 (2013) 945–951, https://doi.org/10.1016/j.actamat.2012.10.042.

[216] M.S. Kang, C.-H. Lee, J.B. Park, H. Yoo, G.-C. Yi, Gallium nitride nanostructures for light-emitting diode applications, Nano Energy 1 (2012) 391–400, https://doi.org/10.1016/j.nanoen.2012.03.005.

[217] C. Zhou, A. Ghods, V.G. Saravade, P.V. Patel, K.L. Yunghans, C. Ferguson, Y. Feng, B. Kucukgok, N. Lu, I.T. Ferguson, Review—the current and emerging applications of the III-nitrides, ECS J. Solid State Sci. Technol. 6 (2017) Q149–Q156, https://doi.org/10.1149/2.0101712jss.

[218] T. Kente, S.D. Mhlanga, Gallium nitride nanostructures: synthesis, characterization and applications, J. Cryst. Growth 444 (2016) 55–72, https://doi.org/10.1016/j.jcrysgro.2016.03.033.

[219] M.S. Shur, GaN based transistors for high power applications, Solid State Electron 42 (1998) 2131–2138, https://doi.org/10.1016/S0038-1101(98)00208-1.

[220] M.A. Khan, G. Simin, S.G. Pytel, A. Monti, E. Santi, J.L. Hudgins, New Developments in Gallium Nitride and the Impact on Power Electronics, in: IEEE 36th Conference on Power Electronics Specialists, 2005., IEEE, n.d.: pp. 15–26. https://doi.org/10.1109/PESC.2005.1581596.

[221] O. Ambacher, Growth and applications of Group III-nitrides, J. Phys. D. Appl. Phys. 31 (1998) 2653–2710, https://doi.org/10.1088/0022-3727/31/20/001.

[222] S.P. DenBaars, D. Feezell, K. Kelchner, S. Pimputkar, C.-C. Pan, C.-C. Yen, S. Tanaka, Y. Zhao, N. Pfaff, R. Farrell, M. Iza, S. Keller, U. Mishra, J.S. Speck, S. Nakamura, Development of gallium-nitride-based light-emitting diodes (LEDs) and laser diodes for energy-efficient lighting and displays, Acta Mater. 61 (2013) 945–951, https://doi.org/10.1016/j.actamat.2012.10.042.

[223] H.S. Wasisto, J.D. Prades, J. Gülink, A. Waag, Beyond solid-state lighting: miniaturization, hybrid integration, and applications of GaN nano- and micro-LEDs, Appl. Phys. Rev. 6 (2019), https://doi.org/10.1063/1.5096322.

[224] S. Nakamura, M.R. Krames, History of gallium–nitride-based light-emitting diodes for illumination, Proc. IEEE 101 (2013) 2211–2220, https://doi.org/10.1109/JPROC.2013.2274929.

[225] A.R. Anwar, M.T. Sajjad, M.A. Johar, C.A. Hernández-Gutiérrez, M. Usman, S. P. Łepkowski, Recent progress in Micro-LED-based display technologies, Laser Photon Rev. 16 (2022), https://doi.org/10.1002/lpor.202100427.

[226] Y. Wu, J. Ma, P. Su, L. Zhang, B. Xia, Full-color realization of micro-LED displays, Nanomaterials 10 (2020) 2482, https://doi.org/10.3390/nano10122482.

[227] J. Herrnsdorf, J.J.D. McKendry, Shuailong Zhang, Enyuan Xie, R. Ferreira, D. Massoubre, A.M. Zuhdi, R.K. Henderson, I. Underwood, S. Watson, A.E. Kelly, E. Gu, M.D. Dawson, Active-matrix GaN micro light-emitting diode display with unprecedented brightness, IEEE Trans. Electron Devices 62 (2015) 1918–1925, https://doi.org/10.1109/TED.2015.2416915.

[228] J. Ryu, S. Park, Y. Park, S. Ryu, K. Hwang, H.W. Jang, Technological breakthroughs in chip fabrication, transfer, and color conversion for high-performance micro-LED displays, Adv. Mater. 35 (2023), https://doi.org/10.1002/adma.202204947.

[229] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, H. Morkoç, Micro-LEDs, a manufacturability perspective, Appl. Sci. 9 (2019) 1206, https://doi.org/10.3390/app9061206.

[230] Z. Wang, X. Shan, X. Cui, P. Tian, Characteristics and techniques of GaN-based micro-LEDs for application in next-generation display, J. Semicond. 41 (2020) 041606, https://doi.org/10.1088/1674-4926/41/4/041606.

[231] I. Akasaki, H. Amano, Breakthroughs in improving crystal quality of GaN and invention of the p–n junction blue-light-emitting diode, Jpn J. Appl. Phys. 45 (2006) 9001, https://doi.org/10.1143/JJAP.45.9001.

[232] F. Shahedipour-Sandvik, M. Tungare, J. Leathersich, P. Suvarna, R. Tompkins, K. A. Jones, III-Nitride devices on Si: challenges and opportunities, in: 2011 International Semiconductor Device Research Symposium (ISDRS), IEEE, 2011, pp. 1–2, https://doi.org/10.1109/ISDRS.2011.6135260.

[233] H.-V. Han, H.-Y. Lin, C.-C. Lin, W.-C. Chong, J.-R. Li, K.-J. Chen, P. Yu, T.-M. Chen, H.-M. Chen, K.-M. Lau, H.-C. Kuo, Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology, Opt. Express 23 (2015) 32504, https://doi.org/10.1364/OE.23.032504.

[234] A. Liudi Mulyo, Y. Konno, J.S. Nilsen, A.T.J. van Helvoort, B.-O. Fimland, H. Weman, K. Kishino, Growth study of self-assembled GaN nanocolumns on silica glass by plasma assisted molecular beam epitaxy, J. Cryst. Growth 480 (2017) 67–73, https://doi.org/10.1016/j.jcrysgro.2017.10.009.

[235] Y.-L. Chang, F. Li, A. Fatehi, Z. Mi, Molecular beam epitaxial growth and characterization of non-tapered InN nanowires on Si(111), Nanotechnology 20 (2009) 345203, https://doi.org/10.1088/0957-4484/20/34/345203.

[236] Y.J. Hong, C. Lee, A. Yoon, M. Kim, H. Seong, H.J. Chung, C. Sone, Y.J. Park, G. Yi, Visible-color-tunable light-emitting diodes, Adv. Mater. 23 (2011) 3284–3288, https://doi.org/10.1002/adma.201100806.

[237] H.P.T. Nguyen, K. Cui, S. Zhang, S. Fathololoumi, Z. Mi, Full-color InGaN/GaN dot-in-a-wire light emitting diodes on silicon, Nanotechnology 22 (2011) 445202, https://doi.org/10.1088/0957-4484/22/44/445202.

[238] H.Q.T. Bui, R.T. Velpula, B. Jain, H.P.T. Nguyen, Full-color microLEDs for display technologies. in: Conference on Lasers and Electro-Optics, Optica Publishing Group,, Washington, D.C., 2020, p. ATh3I.4, https://doi.org/10.1364/CLEO_AT.2020.ATh3I.4.

[239] X. Liu, Y. Wu, Y. Malhotra, Y. Sun, Y. Ra, R. Wang, M. Stevenson, S. Coe-Sullivan, Z. Mi, Submicron full-color LED pixels for microdisplays and micro-LED main displays, J. Soc. Inf. Disp. 28 (2020) 410–417, https://doi.org/10.1002/jsid.899.

[240] Y.-H. Ra, R. Wang, S.Y. Woo, M. Djavid, S.Md Sadaf, J. Lee, G.A. Botton, Z. Mi, Full-color single nanowire pixels for projection displays, Nano Lett. 16 (2016) 4608–4615, https://doi.org/10.1021/acs.nanolett.6b01929.

[241] S.-W. Huang Chen, C.-C. Shen, T. Wu, Z.-Y. Liao, L.-F. Chen, J.-R. Zhou, C.-F. Lee, C.-H. Lin, C.-C. Lin, C.-W. Sher, P.-T. Lee, A.-J. Tzou, Z. Chen, H.-C. Kuo, Full-color monolithic hybrid quantum dot nanoring micro light-emitting diodes with improved efficiency using atomic layer deposition and nonradiative resonant energy transfer, Photonics Res 7 (2019) 416, https://doi.org/10.1364/PRJ.7.000416.

[242] S.-W. Wang, K.-B. Hong, Y.-L. Tsai, C.-H. Teng, A.-J. Tzou, Y.-C. Chu, P.-T. Lee, P.-C. Ku, C.-C. Lin, H.-C. Kuo, Wavelength tunable InGaN/GaN nano-ring LEDs via nano-sphere lithography, Sci. Rep. 7 (2017) 42962, https://doi.org/10.1038/srep42962.

[243] H.-Y. Lin, C.-W. Sher, D.-H. Hsieh, X.-Y. Chen, H.-M.P. Chen, T.-M. Chen, K.-M. Lau, C.-H. Chen, C.-C. Lin, H.-C. Kuo, Optical cross-talk reduction in a quantum-dot-based full-color micro-light-emitting-diode display by a lithographic-fabricated photoresist mold, Photonics Res 5 (2017) 411, https://doi.org/10.1364/PRJ.5.000411.

[244] D. Zhou, Y. Wang, P. Tian, P. Jing, M. Sun, X. Chen, X. Xu, D. Li, S. Mei, X. Liu, W. Zhang, R. Guo, S. Qu, H. Zhang, Microwave-assisted heating method toward multicolor quantum dot-based phosphors with much improved luminescence, ACS Appl. Mater. Interfaces 10 (2018) 27160–27170, https://doi.org/10.1021/acsami.8b06323.

[245] S.-J. Ho, H.-C. Hsu, C.-W. Yeh, H.-S. Chen, Inkjet-printed salt-encapsulated quantum dot film for UV-Based RGB color-converted micro-light emitting diode displays, ACS Appl. Mater. Interfaces 12 (2020) 33346–33351, https://doi.org/10.1021/acsami.0c05646.

[246] X. Bai, H. Yang, B. Zhao, X. Zhang, X. Li, B. Xu, F. Wei, Z. Liu, K. Wang, X.W. Sun, 4-4: flexible quantum dot color converter film for micro-LED applications, SID Symp. . Dig. Tech. Pap. 50 (2019) 30–33, https://doi.org/10.1002/sdtp.12848.

[247] G.-S. Chen, B.-Y. Wei, C.-T. Lee, H.-Y. Lee, Monolithic red/green/blue micro-LEDs with HBR and DBR structures, IEEE Photonics Technol. Lett. 30 (2018) 262–265, https://doi.org/10.1109/LPT.2017.2786737.

[248] F. Gou, E. Hsiang, G. Tan, Y. Lan, C. Tsai, S. Wu, High performance color-converted micro-LED displays, J. Soc. Inf. Disp. 27 (2019) 199–206, https://doi.org/10.1002/jsid.764.

[249] J.-H. Kang, B. Li, T. Zhao, M.A. Johar, C.-C. Lin, Y.-H. Fang, W.-H. Kuo, K.-L. Liang, S. Hu, S.-W. Ryu, J. Han, RGB arrays for micro-light-emitting diode applications using nanoporous GaN embedded with quantum dots, ACS Appl. Mater. Interfaces 12 (2020) 30890–30895, https://doi.org/10.1021/acsami.0c00839.

[250] J.-H. Kang, J. Han, 65-2: *Invited Paper:* enabling technology for microLED display based on quantum dot color converter, SID Symp. . Dig. Tech. Pap. 50 (2019) 914–916, https://doi.org/10.1002/sdtp.13073.

[251] Z.J. Liu, W.C. Chong, K.M. Wong, K.H. Tam, K.M. Lau, A novel BLU-free full-color LED projector using LED on silicon micro-displays, IEEE Photonics Technol. Lett. 25 (2013) 2267–2270, https://doi.org/10.1109/LPT.2013.2285229.

[252] W.C. Chong, K.M. Wong, Z.J. Liu, K.M. Lau, 60.4: a novel full-color 3LED projection system using R-G-B light emitting diodes on silicon (LEDoS) micro-displays, SID Symp. . Dig. Tech. Pap. 44 (2013) 838–841, https://doi.org/10.1002/j.2168-0159.2013.tb06348.x.

[253] J.M.M. Santos, B.E. Jones, P.J. Schlosser, S. Watson, J. Herrnsdorf, B. Guilhabert, J.J.D. McKendry, J. De Jesus, T.A. Garcia, M.C. Tamargo, A.E. Kelly, J.E. Hastie, N. Laurand, M.D. Dawson, Hybrid GaN LED with capillary-bonded II–VI MQW color-converting membrane for visible light communications, Semicond. Sci. Technol. 30 (2015) 035012, https://doi.org/10.1088/0268-1242/30/3/035012.

[254] S. Zhang, Z. Gong, J.J.D. McKendry, S. Watson, A. Cogman, E. Xie, P. Tian, E. Gu, Z. Chen, G. Zhang, A.E. Kelly, R.K. Henderson, M.D. Dawson, CMOS-controlled color-tunable smart display, IEEE Photonics J. 4 (2012) 1639–1646, https://doi.org/10.1109/JPHOT.2012.2212181.

[255] H.S. El-Ghoroury, M. Yeh, J.C. Chen, X. Li, C.-L. Chuang, Growth of monolithic full-color GaN-based LED with intermediate carrier blocking layers, AIP Adv. 6 (2016), https://doi.org/10.1063/1.4959897.

[256] S. Nakamura, T. Mukai, M.S. Masayuki Senoh, N.I. Naruhito Iwasa, Thermal annealing effects on P-type Mg-doped GaN films, Jpn J. Appl. Phys. 31 (1992) L139, https://doi.org/10.1143/JJAP.31.L139.

[257] S.N. Shuji Nakamura, T.M. Takashi Mukai, High-quality InGaN films grown on GaN films, Jpn J. Appl. Phys. 31 (1992) L1457, https://doi.org/10.1143/JJAP.31.L1457.
[258] S. Nakamura, M.S. Masayuki Senoh, T.M. Takashi Mukai, P-GaN/N-InGaN/N-GaN double-heterostructure blue-light-emitting diodes, Jpn J. Appl. Phys. 32 (1993) L8, https://doi.org/10.1143/JJAP.32.L8.
[259] S. Nakamura, T. Mukai, M. Senoh, Candela-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting diodes, Appl. Phys. Lett. 64 (1994) 1687–1689, https://doi.org/10.1063/1.111832.
[260] S. Nakamura, M. Senoh, N. Iwasa, S.N. Shin-ichi Nagahama, High-Brightness InGaN blue, green and yellow light-emitting diodes with quantum well structures, Jpn J. Appl. Phys. 34 (1995) L797, https://doi.org/10.1143/JJAP.34.L797.
[261] D. Ehrentraut, R.T. Pakalapati, D.S. Kamber, W. Jiang, D.W. Pocius, B.C. Downey, M. McLaurin, M.P. D'Evelyn, High quality, low cost ammonothermal bulk GaN substrates, Jpn J. Appl. Phys. 52 (2013) 08JA01, https://doi.org/10.7567/JJAP.52.08JA01.
[262] R. Dwiliński, R. Doradziński, J. Garczyński, L.P. Sierzputowski, A. Puchalski, Y. Kanbara, K. Yagi, H. Minakuchi, H. Hayashi, Excellent crystallinity of truly bulk ammonothermal GaN, J. Cryst. Growth 310 (2008) 3911–3916, https://doi.org/10.1016/j.jcrysgro.2008.06.036.
[263] T. Yoshida, Y. Oshima, T. Eri, K. Ikeda, S. Yamamoto, K. Watanabe, M. Shibata, T. Mishima, Fabrication of 3-in GaN substrates by hydride vapor phase epitaxy using void-assisted separation method, J. Cryst. Growth 310 (2008) 5–7, https://doi.org/10.1016/j.jcrysgro.2007.10.014.
[264] A. Chakraborty, B.A. Haskell, S. Keller, J.S. Speck, S.P. Denbaars, S. Nakamura, U. K. Mishra, Demonstration of nonpolar M-plane InGaN/GaN light-emitting diodes on free-standing m-plane GaN substrates, Jpn J. Appl. Phys. 44 (2005) L173, https://doi.org/10.1143/JJAP.44.L173.
[265] Y. Narukawa, M. Ichikawa, D. Sanga, M. Sano, T. Mukai, White light emitting diodes with super-high luminous efficacy, J. Phys. D. Appl. Phys. 43 (2010) 354002, https://doi.org/10.1088/0022-3727/43/35/354002.
[266] M.J. Cich, R.I. Aldaz, A. Chakraborty, A. David, M.J. Grundmann, A. Tyagi, M. Zhang, F.M. Steranka, M.R. Krames, Bulk GaN based violet light-emitting diodes with high efficiency at very high current density, Appl. Phys. Lett. 101 (2012) 223509, https://doi.org/10.1063/1.4769228.
[267] O.B. Shchekin, J.E. Epler, T.A. Trottier, T. Margalith, D.A. Steigerwald, M. O. Holcomb, P.S. Martin, M.R. Krames, High performance thin-film flip-chip InGaN–GaN light-emitting diodes, Appl. Phys. Lett. 89 (2006), https://doi.org/10.1063/1.2337007.
[268] J. Hertkorn, S.B. Thapa, T. Wunderer, F. Scholz, Z.H. Wu, Q.Y. Wei, F.A. Ponce, M.A. Moram, C.J. Humphreys, C. Vierheilig, U.T. Schwarz, Highly conductive modulation doped composition graded p-AlGaN/(AlN)/GaN multiheterostructures grown by metalorganic vapor phase epitaxy, J. Appl. Phys. 106 (2009), https://doi.org/10.1063/1.3160312.
[269] C. Weisbuch, M. Piccardo, L. Martinelli, J. Iveland, J. Peretti, J.S. Speck, The efficiency challenge of nitride light-emitting diodes for lighting, Phys. Status Solidi (a) 212 (2015) 899–913, https://doi.org/10.1002/pssa.201431868.
[270] J.Y. Tsao, M.H. Crawford, M.E. Coltrin, A.J. Fischer, D.D. Koleske, G. S. Subramania, G.T. Wang, J.J. Wierer, R.F. Karlicek, Toward smart and ultra-efficient solid-state lighting, Adv. Opt. Mater. 2 (2014) 809–836, https://doi.org/10.1002/adom.201400131.
[271] J.M. Phillips, M.E. Coltrin, M.H. Crawford, A.J. Fischer, M.R. Krames, R. Mueller-Mach, G.O. Mueller, Y. Ohno, L.E.S. Rohwer, J.A. Simmons, J.Y. Tsao, Research challenges to ultra-efficient inorganic solid-state lighting, Laser Photon Rev. 1 (2007) 307–333, https://doi.org/10.1002/lpor.200710019.
[272] M. Kneissl, T.-Y. Seong, J. Han, H. Amano, The emergence and prospects of deep-ultraviolet light-emitting diode technologies, Nat. Photonics 13 (2019) 233–244, https://doi.org/10.1038/s41566-019-0359-9.
[273] Z. Ren, H. Yu, Z. Liu, D. Wang, C. Xing, H. Zhang, C. Huang, S. Long, H. Sun, Band engineering of III-nitride-based deep-ultraviolet light-emitting diodes: a review, J. Phys. D. Appl. Phys. 53 (2020) 073002, https://doi.org/10.1088/1361-6463/ab4d7b.
[274] M.S. Wong, S. Nakamura, S.P. DenBaars, Review—progress in high performance III-nitride micro-light-emitting diodes, ECS J. Solid State Sci. Technol. 9 (2020) 015012, https://doi.org/10.1149/2.0302001JSS.
[275] C.-L. Liao, Y.-F. Chang, C.-L. Ho, M.-C. Wu, High-speed GaN-based blue light-emitting diodes with gallium-doped ZnO current spreading layer, IEEE Electron Device Lett. 34 (2013) 611–613, https://doi.org/10.1109/LED.2013.2252457.
[276] J.J.D. McKendry, R.P. Green, A.E. Kelly, Z. Gong, B. Guilhabert, D. Massoubre, E. Gu, M.D. Dawson, High-speed visible light communications using individual pixels in a micro light-emitting diode array, IEEE Photonics Technol. Lett. 22 (2010) 1346–1348, https://doi.org/10.1109/LPT.2010.2056360.
[277] Chien-Lan Liao, Chong-Lung Ho, Yung-Fu Chang, Chi-Hung Wu, Meng-Chyi Wu, High-speed light-emitting diodes emitting at 500 nm With 463-MHz modulation bandwidth, IEEE Electron Device Lett. 35 (2014) 563–565, https://doi.org/10.1109/LED.2014.2304513.
[278] S. Rajbhandari, J.J.D. McKendry, J. Herrnsdorf, H. Chun, G. Faulkner, H. Haas, I. M. Watson, D. O'Brien, M.D. Dawson, A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications, Semicond. Sci. Technol. 32 (2017) 023001, https://doi.org/10.1088/1361-6641/32/2/023001.
[279] M.S. Wong, S. Nakamura, S.P. DenBaars, Review—progress in high performance III-nitride micro-light-emitting diodes, ECS J. Solid State Sci. Technol. 9 (2020) 015012, https://doi.org/10.1149/2.0302001JSS.
[280] S. Islam, V. Protasenko, S. Rouvimov, J. Verma, H. Xing, D. Jena, Deep-UV LEDs using polarization-induced doping: electroluminescence at cryogenic temperatures, in: 2015 73rd Annual Device Research Conference (DRC), IEEE,, 2015, pp. 67–68, https://doi.org/10.1109/DRC.2015.7175559.
[281] M. Chlipala, H. Turski, M. Siekacz, K. Pieniak, K. Nowakowski-Szkudlarek, T. Suski, C. Skierbiszewski, Nitride light-emitting diodes for cryogenic temperatures, Opt. Express 28 (2020) 30299, https://doi.org/10.1364/OE.403906.
[282] M.-H. Kim, M.F. Schubert, Q. Dai, J.K. Kim, E.F. Schubert, J. Piprek, Y. Park, Origin of efficiency droop in GaN-based light-emitting diodes, Appl. Phys. Lett. 91 (2007), https://doi.org/10.1063/1.2800290.
[283] T. Wu, C.-W. Sher, Y. Lin, C.-F. Lee, S. Liang, Y. Lu, S.-W. Huang Chen, W. Guo, H.-C. Kuo, Z. Chen, Mini-LED and micro-LED: promising candidates for the next generation display technology, Appl. Sci. 8 (2018) 1557, https://doi.org/10.3390/app8091557.
[284] Y. Lin, W. Huang, M. Zhanghu, Z. Liu, P-8.4: The full-color micro-LED based on quantum dots inkjet printing, SID Symp. . Dig. Tech. Pap. 53 (2022) 882–883, https://doi.org/10.1002/sdtp.16128.
[285] W. Rong, Z. Liu, P-10.10: high PPI patterned PDMS stamp used in micro-LED massive transfer, SID Symp. . Dig. Tech. Pap. 54 (2023) 815–816, https://doi.org/10.1002/sdtp.16421.
[286] N. Tansu, H. Zhao, G. Liu, X.-H. Li, J. Zhang, H. Tong, Y.-K. Ee, III-Nitride Photonics, IEEE Photonics J. 2 (2010) 241–248, https://doi.org/10.1109/JPHOT.2010.2045887.
[287] J.C. Campbell, S. Demiguel, F. Ma, A. Beck, X. Guo, S. Wang, X. Zheng, X. Li, J. D. Beck, M.A. Kinch, A. Huntington, L.A. Coldren, J. Decobert, N. Tscherptner, Recent advances in avalanche photodiodes, IEEE J. Sel. Top. Quantum Electron. 10 (2004) 777–787, https://doi.org/10.1109/JSTQE.2004.833971.
[288] A. Pandey, Y. Malhotra, P. Wang, K. Sun, X. Liu, Z. Mi, N-polar InGaN/GaN nanowires: overcoming the efficiency cliff of red-emitting micro-LEDs, Photonics Res 10 (2022), https://doi.org/10.1364/prj.450465.
[289] A. Pandey, J. Min, M. Reddeppa, Y. Malhotra, Y. Xiao, Y. Wu, K. Sun, Z. Mi, An ultrahigh efficiency excitonic micro-LED, Nano Lett. 23 (2023), https://doi.org/10.1021/acs.nanolett.2c04220.
[290] J. Li, N. Gao, D. Cai, W. Lin, K. Huang, S. Li, J. Kang, Multiple fields manipulation on nitride material structures in ultraviolet light-emitting diodes, Light Sci. Appl. 10 (2021), https://doi.org/10.1038/s41377-021-00563-0.
[291] S.S. Pasayat, C. Gupta, M.S. Wong, R. Ley, M.J. Gordon, S.P. Denbaars, S. Nakamura, S. Keller, U.K. Mishra, Demonstration of ultra-small (<10 μm) 632 nm red InGaN micro-LEDs with useful on-wafer external quantum efficiency (>0.2%) for mini-displays, Appl. Phys. Express 14 (2021), https://doi.org/10.35848/1882-0786/abd06f.
[292] Z. Zhuang, D. Iida, K. Ohkawa, Ultrasmall and ultradense InGaN-based RGB monochromatic micro-light-emitting diode arrays by pixilation of conductive p-GaN, Photonics Res 9 (2021), https://doi.org/10.1364/prj.439741.
[293] S. Yuvaraja, V. Khandelwal, X. Tang, X. Li, Wide bandgap semiconductor-based integrated circuits, Chip (2023) 100072, https://doi.org/10.1016/j.chip.2023.100072.
[294] M.A. Triana, E.-L. Hsiang, C. Zhang, Y. Dong, S.-T. Wu, Luminescent nanomaterials for energy-efficient display and healthcare, ACS Energy Lett. 7 (2022) 1001–1020, https://doi.org/10.1021/acsenergylett.1c02745.
[295] G. Jang, H. Han, S. Ma, J. Lee, C. Uk Lee, W. Jeong, J. Son, D. Cho, J.-H. Kim, C. Park, J. Moon, Rapid crystallization-driven high-efficiency phase-pure deep-blue Ruddlesden–Popper perovskite light-emitting diodes, Adv. Photonics 5 (2023), https://doi.org/10.1117/1.AP.5.1.016001.
[296] B. Guo, R. Lai, S. Jiang, L. Zhou, Z. Ren, Y. Lian, P. Li, X. Cao, S. Xing, Y. Wang, W. Li, C. Zou, M. Chen, Z. Hong, C. Li, B. Zhao, D. Di, Ultrastable near-infrared perovskite light-emitting diodes, Nat. Photonics 16 (2022) 637–643, https://doi.org/10.1038/s41566-022-01046-3.
[297] C. Zhao, T.K. Ng, N. Wei, A. Prabaswara, M.S. Alias, B. Janjua, C. Shen, B.S. Ooi, Facile formation of high-quality InGaN/GaN quantum-disks-in-nanowires on bulk-metal substrates for high-power light-emitters, Nano Lett. 16 (2016), https://doi.org/10.1021/acs.nanolett.5b04190.
[298] C. Zhao, M. Ebaid, H. Zhang, D. Priante, B. Janjua, D. Zhang, N. Wei, A. A. Alhamoud, M.K. Shakfa, T.K. Ng, B.S. Ooi, Quantified hole concentration in AlGaN nanowires for high-performance ultraviolet emitters, Nanoscale 10 (2018), https://doi.org/10.1039/c8nr02615g.
[299] S. Zhao, A.T. Connie, M.H.T. Dastjerdi, X.H. Kong, Q. Wang, M. Djavid, S. Sadaf, X.D. Liu, I. Shih, H. Guo, Z. Mi, Aluminum nitride nanowire light emitting diodes: Breaking the fundamental bottleneck of deep ultraviolet light sources, Sci. Rep. 5 (2014), https://doi.org/10.1038/srep08332.
[300] K. Kishino, T. Hoshino, S. Ishizawa, A. Kikuchi, Selective-area growth of GaN nanocolumns on titanium-mask-patterned silicon (111) substrates by RF-plasma-assisted molecular-beam epitaxy, Electron Lett. 44 (2008), https://doi.org/10.1049/el:20081323.
[301] M. Nami, R.F. Eller, S. Okur, A.K. Rishinaramangalam, S. Liu, I. Brener, D. F. Feezell, Tailoring the morphology and luminescence of GaN/InGaN core-shell nanowires using bottom-up selective-area epitaxy, Nanotechnology 28 (2017), https://doi.org/10.1088/0957-4484/28/2/025202.
[302] K. Kishino, S. Ishizawa, Selective-area growth of GaN nanocolumns on Si(111) substrates for application to nanocolumn emitters with systematic analysis of dislocation filtering effect of nanocolumns, Nanotechnology 26 (2015), https://doi.org/10.1088/0957-4484/26/22/225602.
[303] Z. Wang, X. Shan, X. Cui, P. Tian, Characteristics and techniques of GaN-based micro-LEDs for application in next-generation display, J. Semicond. 41 (2020) 041606, https://doi.org/10.1088/1674-4926/41/4/041606.
[304] P. Feng, C. Xu, J. Bai, C. Zhu, I. Farrer, G.M. De Arriba, T. Wang, A simple approach to achieving ultrasmall III-nitride microlight-emitting diodes with red

emission, ACS Appl. Electron Mater. 4 (2022), https://doi.org/10.1021/acsaelm.2c00311.
[305] Y. Cai, J.I.H. Haggar, C. Zhu, P. Feng, J. Bai, T. Wang, Direct epitaxial approach to achieve a monolithic on-chip integration of a HEMT and a single micro-LED with a high-modulation bandwidth, ACS Appl. Electron Mater. 3 (2021), https://doi.org/10.1021/acsaelm.0c00985.
[306] J.B. Wright, S. Liu, G.T. Wang, Q. Li, A. Benz, D.D. Koleske, P. Lu, H. Xu, L. Lester, T.S. Luk, I. Brener, G. Subramania, Multi-colour nanowire photonic crystal laser pixels, Sci. Rep. 3 (2013), https://doi.org/10.1038/srep02982.
[307] D. Elfström, B. Guilhabert, J. McKendry, S. Poland, Z. Gong, D. Massoubre, E. Richardson, B.R. Rae, G. Valentine, G. Blanco-Gomez, E. Gu, J.M. Cooper, R. K. Henderson, M.D. Dawson, Mask-less ultraviolet photolithography based on CMOS-driven micro-pixel light emitting diodes, Opt. Express 17 (2009), https://doi.org/10.1364/oe.17.023522.
[308] W. Wei, C. Zhou, X. Nie, G. Zhang, Z. Chen, Anti-crosstalk device based on a Novel Micro-LED structure design, Micro Nanostruct. 182 (2023), https://doi.org/10.1016/j.micrna.2023.207631.
[309] J. Ye, Y. Peng, C. Luo, H. Wang, X. Zhou, T. Guo, J. Sun, Q. Yan, Y. Zhang, C. Wu, Pixelation of GaN based Micro-LED arrays by tailoring injection energy and dose of fluorine ion implantation, J. Lumin 261 (2023), https://doi.org/10.1016/j.jlumin.2023.119903.
[310] Y. Yin, R. Chen, R. He, Y. Duo, H. Long, W. Hu, J. Zhai, C. Pan, Z. Zhang, J. Wang, J. Li, T. Wei, Strain visualization enabled in dual-wavelength InGaN/GaN multiple quantum wells Micro-LEDs by piezo-phototronic effect, Nano Energy 109 (2023), https://doi.org/10.1016/j.nanoen.2023.108283.
[311] S. Liu, S. Han, C. Xu, H. Xu, X. Wang, D. Wang, Y. Zhu, Enhanced photoelectric performance of GaN-based Micro-LEDs by ion implantation, Opt. Mater. (Amst.) 121 (2021), https://doi.org/10.1016/j.optmat.2021.111579.
[312] K.P. Chang, C.J. Wu, C.W. Lo, Y.S. Lin, C.C. Yen, D.S. Wuu, Synthesis of SiO2-coated CdSe/ZnS quantum dots using various dispersants in the photoresist for color-conversion micro-LED displays, Mater. Sci. Semicond. Process 148 (2022), https://doi.org/10.1016/j.mssp.2022.106790.
[313] M. Vidhya, N. Sumathi, K. Sadaiyandi, P. Rajapandi, K. Elumalai, S. Arunkumar, A.N. Mary, R. Marnadu, F.S. Khan, Mohd Shkir, Effect of molar concentration on optoelectronic properties of NiO nanoparticles for p-n junction diode application, Sens Actuators A Phys. 366 (2024) 114995, https://doi.org/10.1016/j.sna.2023.114995.
[314] J. Li, J. Qiu, B. Xie, W. Li, K. Wang, C.H. Suk, C. Wu, Y. Yu, Y. Ye, X. Zhou, Y. Zhang, T. Guo, T.W. Kim, Light-emitting MOS junction for ultrahigh-resolution quantum dot displays, Nano Energy 120 (2024) 109105, https://doi.org/10.1016/j.nanoen.2023.109105.
[315] M. Xi, F. Liu, X. Zhu, Y. Li, L. Bai, X. Chen, Y. Gong, Y. Guo, Y. Zhou, L. Peng, J. Kang, Y. Cao, X. Liang, High-performance thin-film transistors based on aligned carbon nanotubes for mini- and micro-LED displays, Carbon N. Y 218 (2024) 118718, https://doi.org/10.1016/j.carbon.2023.118718.
[316] S.S. Majani, R.B. Basavaraj, K.N. Venkatachalaiah, T. Chandrasekhar, S.P. Kollur, Versatile deep red-emitting SrCeO3: Eu3+ nanopowders for display devices and advanced forensic applications, J. Solid State Chem. 329 (2024) 124360, https://doi.org/10.1016/j.jssc.2023.124360.
[317] Y. Hu, Y. Ye, W. Zhang, K. Li, Y. Zhou, Y. Zhang, Z. Deng, J. Han, X. Zhao, C. Liu, Laser-induced inverted patterning of nanocrystals embedded glass for micro-light-emitting diodes, J. Mater. Sci. Technol. 150 (2023), https://doi.org/10.1016/j.jmst.2022.11.055.
[318] J. Chen, D. Li, Y. Sun, Y. Wang, Z. Zeng, L. Jiang, L. Chi, Sub-micro organic light emitting diode arrays defined by tip-induced resist hollow structures, Appl. Surf. Sci. 638 (2023), https://doi.org/10.1016/j.apsusc.2023.158033.
[319] T. Wang, X. Zhang, Y. Liu, W. Chong, Z. Huang, Z. Lu, X. Zhang, W. Shi, Q. Wang, Z. zeng, B. Zhang, GaN-on-Si micro resonant-cavity light-emitting diodes with dielectric and metal mirrors, Opt. Mater. (Amst.) 143 (2023), https://doi.org/10.1016/j.optmat.2023.114096.
[320] K. Kim, G. Jung, J. Kim, Y. Sung, J. Kang, W.J. Lee, Y. Moon, T. Jeong, J.H. Song, Correlation between photoluminescence and electroluminescence in GaN-related micro light emitting diodes: Effects of leakage current, applied bias, incident light absorption and carrier escape, Opt. Mater. (Amst.) 120 (2021), https://doi.org/10.1016/j.optmat.2021.111448.
[321] H.Y. Chou, C.W. Lo, K.P. Chang, W.Y. Shi, C.C. Yen, D.S. Wuu, Synthesis of SiO2-coated perovskite quantum dots for micro-LED display applications, Surf. Interfaces 38 (2023), https://doi.org/10.1016/j.surfin.2023.102802.
[322] S. Wang, H. Wang, D. Zhang, Y. Dou, W. Li, F. Cao, L. Yin, L. Wang, Z.J. Zhang, J. Zhang, X. Yang, Perovskite nanocrystals-polymer composites with a micro/nano structured superhydrophobic surface for stable and efficient white light-emitting diodes, Chem. Eng. J. 437 (2022), https://doi.org/10.1016/j.cej.2022.135303.
[323] Y. Kanemitsu, T. Handa, Photophysics of metal halide perovskites: From materials to devices, Jpn J. Appl. Phys. 57 (2018), https://doi.org/10.7567/JJAP.57.090101.
[324] H. Wang, Y. Sun, J. Chen, F. Wang, R. Han, C. Zhang, J. Kong, L. Li, J. Yang, A review of perovskite-based photodetectors and their applications, Nanomaterials 12 (2022), https://doi.org/10.3390/nano12244390.
[325] Q. Dong, L. Lei, J. Mendes, F. So, Operational stability of perovskite light emitting diodes, JPhys Mater. 3 (2020), https://doi.org/10.1088/2515-7639/ab60c4.
[326] S. Wang, A.A. Yousefi Amin, L. Wu, M. Cao, Q. Zhang, T. Ameri, Perovskite nanocrystals: synthesis, stability, and optoelectronic applications, Small Struct. 2 (2021), https://doi.org/10.1002/sstr.202000124.
[327] A.B. Djurišić, F.Z. Liu, H.W. Tam, M.K. Wong, A. Ng, C. Surya, W. Chen, Z.B. He, Perovskite solar cells - an overview of critical issues, Prog. Quantum Electron 53 (2017), https://doi.org/10.1016/j.pquantelec.2017.05.002.
[328] V. Murugadoss, D.Y. Kang, W.J. Lee, I.G. Jang, T. Geun Kim, Fluorine-induced surface modification to obtain stable and low energy loss zinc oxide/perovskite interface for photovoltaic application, Adv. Compos Hybrid. Mater. 5 (2022), https://doi.org/10.1007/s42114-022-00498-z.
[329] J. Cai, X. Chen, W. Zhang, L. Yang, Z. Lin, W. Zhao, Y. Ye, S. Xu, T. Guo, E. Chen, Two-step performance optimization of CsPbBr3 perovskite nanocrystals for wide color gamut displays, Photonics 10 (2023) 1113, https://doi.org/10.3390/photonics10101113.
[330] W. Wang, R. Guo, X. Xiong, H. Liu, W. Chen, S. Hu, E. Amador, B. Chen, X. Zhang, L. Wang, Improved stability and efficiency of perovskite via a simple solid diffusion method, Mater. Today Phys. 18 (2021) 100374, https://doi.org/10.1016/j.mtphys.2021.100374.
[331] H.J. An, M.S. Kim, J.-M. Myoung, Strategy for the fabrication of perovskite-based green micro LED for ultra high-resolution displays by micro-molding process and surface passivation, Chem. Eng. J. 453 (2023) 139927, https://doi.org/10.1016/j.cej.2022.139927.
[332] C. Hsu, S. Tian, Y. Lian, G. Zhang, Q. Zhou, X. Cao, B. Zhao, D. Di, Efficient mini/micro-perovskite light-emitting diodes, Cell Rep. Phys. Sci. 2 (2021), https://doi.org/10.1016/j.xcrp.2021.100582.
[333] W. Xu, Q. Hu, S. Bai, C. Bao, Y. Miao, Z. Yuan, T. Borzda, A.J. Barker, E. Tyukalova, Z. Hu, M. Kawecki, H. Wang, Z. Yan, X. Liu, X. Shi, K. Uvdal, M. Fahlman, W. Zhang, M. Duchamp, J.M. Liu, A. Petrozza, J. Wang, L.M. Liu, W. Huang, F. Gao, Rational molecular passivation for high-performance perovskite light-emitting diodes, Nat. Photonics 13 (2019), https://doi.org/10.1038/s41566-019-0390-x.
[334] B. Zhao, S. Bai, V. Kim, R. Lamboll, R. Shivanna, F. Auras, J.M. Richter, L. Yang, L. Dai, M. Alsari, X.J. She, L. Liang, J. Zhang, S. Lilliu, P. Gao, H.J. Snaith, J. Wang, N.C. Greenham, R.H. Friend, D. Di, High-efficiency perovskite–polymer bulk heterostructure light-emitting diodes, Nat. Photonics 12 (2018), https://doi.org/10.1038/s41566-018-0283-4.
[335] C. Zou, Y. Liu, D.S. Ginger, L.Y. Lin, Suppressing efficiency roll-off at high current densities for ultra-bright green perovskite light-emitting diodes, ACS Nano 14 (2020), https://doi.org/10.1021/acsnano.0c01817.
[336] C. Zou, C. Chang, D. Sun, K.F. Böhringer, L.Y. Lin, Photolithographic patterning of perovskite thin films for multicolor display applications, Nano Lett. 20 (2020), https://doi.org/10.1021/acs.nanolett.0c00701.
[337] A.I. Alhassan, R.M. Farrell, B. Saifaddin, A. Mughal, F. Wu, S.P. DenBaars, S. Nakamura, J.S. Speck, High luminous efficacy green light-emitting diodes with AlGaN cap layer, Opt. Express 24 (2016), https://doi.org/10.1364/oe.24.017868.
[338] M. Dalla Vecchia, S. Ravyts, G. Van den Broeck, J. Driesen, Gallium-nitride semiconductor technology and its practical design challenges in power electronics applications: an overview, Energies 12 (2019) 2663, https://doi.org/10.3390/en12142663.
[339] S.D. Roh, Production Technology of High Performance III-Nitride Devices. in: Asia Communications and Photonics Conference, OSA, Washington, D.C., 2012, p. ATh4F.2, https://doi.org/10.1364/ACPC.2012.ATh4F.2.
[340] J.A. McDonald, Behind the scenes of GaN development, III-Vs Rev. 10 (1997) 18–23, https://doi.org/10.1016/S0961-1290(97)85647-5.
[341] T. Paskova, D.A. Hanser, K.R. Evans, GaN Substrates for III-Nitride Devices, Proc. IEEE 98 (2010) 1324–1338, https://doi.org/10.1109/JPROC.2009.2030699.
[342] J. Würfl, V. Abrosimova, J. Hilsenbeck, E. Nebauer, W. Rieger, G. Tränkle, Reliability considerations of III-nitride microelectronic devices, Microelectron. Reliab. 39 (1999) 1737–1757, https://doi.org/10.1016/S0026-2714(99)00181-X.
[343] C. Zhao, N. Alfaraj, R. Chandra Subedi, J.W. Liang, A.A. Alatawi, A.A. Alhamoud, M. Ebaid, M.S. Alias, T.K. Ng, B.S. Ooi, III-nitride nanowires on unconventional substrates: from materials to optoelectronic device applications, Prog. Quantum Electron 61 (2018) 1–31, https://doi.org/10.1016/j.pquantelec.2018.07.001.
[344] A. Pandey, Z. Mi, III-Nitride Nanostructures for High Efficiency Micro-LEDs and ultraviolet optoelectronics, IEEE J. Quantum Electron 58 (2022) 1–13, https://doi.org/10.1109/JQE.2022.3151965.
[345] T. Dehghani, Technology commercialization: From generating ideas to creating economic value, Int. J. Organ. Leadersh. 4 (2015) 192–199, https://doi.org/10.33844/ijol.2015.60449.
[346] C.S. Galbraith, A.F. DeNoble, S.B. Ehrlich, Predicting the commercialization progress of early-stage technologies: an ex-ante analysis, IEEE Trans. Eng. Manag 59 (2012) 213–225, https://doi.org/10.1109/TEM.2010.2068050.
[347] A. Arora, A. Gambardella, The Market for Technology, in: 2010: pp. 641–678. https://doi.org/10.1016/S0169-7218(10)01015-4.
[348] D.J. Teece, Capturing value from technological innovation: integration, strategic partnering, and licensing decisions, Interfaces (Provid.) 18 (1988) 46–61, https://doi.org/10.1287/inte.18.3.46.
[349] J. Ryu, S. Park, Y. Park, S. Ryu, K. Hwang, H.W. Jang, Technological breakthroughs in chip fabrication, transfer, and color conversion for high-performance micro-LED displays, Adv. Mater. 35 (2023), https://doi.org/10.1002/adma.202204947.
[350] D.-S. Lee, J.-H. Han, Micro-LED Technology for Display Applications, in: 2021: pp. 271–305. https://doi.org/10.1007/978-981-33-6582-7_12.
[351] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, H. Morkoç, Micro-LEDs, a manufacturability perspective, Appl. Sci. 9 (2019) 1206, https://doi.org/10.3390/app9061206.
[352] F. Chen, J. Bian, J. Hu, N. Sun, B. Yang, H. Ling, H. Yu, K. Wang, M. Gai, Y. Ma, Y. Huang, Mass transfer techniques for large-scale and high-density microLED

arrays, Int. J. Extrem. Manuf. 4 (2022) 042005, https://doi.org/10.1088/2631-7990/ac92ee.
[353] C.A. Bower, S. Bonafede, B. Raymond, A. Pearson, C. Prevatte, T. Weeks, E. Radauscher, E. Vick, C. Verreen, B. Krongard, M.A. Meitl, High-brightness displays made with micro-transfer printed flip-chip microLEDs, in: 2020 IEEE 70th Electronic Components and Technology Conference (ECTC), IEEE,, 2020, pp. 175–181, https://doi.org/10.1109/ECTC32862.2020.00040.
[354] X. Zhou, P. Tian, C.-W. Sher, J. Wu, H. Liu, R. Liu, H.-C. Kuo, Growth, transfer printing and colour conversion techniques towards full-colour micro-LED display, Prog. Quantum Electron 71 (2020) 100263, https://doi.org/10.1016/j.pquantelec.2020.100263.
[355] J. Ryu, S. Park, Y. Park, S. Ryu, K. Hwang, H.W. Jang, Technological breakthroughs in chip fabrication, transfer, and color conversion for high-performance micro-LED displays, Adv. Mater. 35 (2023), https://doi.org/10.1002/adma.202204947.
[356] V.W. Lee, N. Twu, I. Kymissis, Micro-LED technologies and applications, Inf. Disp. (1975) 32 (2016) 16–23, https://doi.org/10.1002/j.2637-496X.2016.tb00949.x.
[357] K. Ding, V. Avrutin, N. Izyumskaya, Ü. Özgür, H. Morkoç, Micro-LEDs, a manufacturability perspective, Appl. Sci. 9 (2019) 1206, https://doi.org/10.3390/app9061206.
[358] R.S. Cok, M. Meitl, R. Rotzoll, G. Melnik, A. Fecioru, A.J. Trindade, B. Raymond, S. Bonafede, D. Gomez, T. Moore, C. Prevatte, E. Radauscher, S. Goodwin, P. Hines, C.A. Bower, Inorganic light-emitting diode displays using micro-transfer printing, J. Soc. Inf. Disp. 25 (2017) 589–609, https://doi.org/10.1002/jsid.610.
[359] J. Ryu, S. Park, Y. Park, S. Ryu, K. Hwang, H.W. Jang, Technological breakthroughs in chip fabrication, transfer, and color conversion for high-performance micro-LED displays, Adv. Mater. 35 (2023), https://doi.org/10.1002/adma.202204947.
[360] L. Ji, G. Zhang, J. Zhang, P. Liu, An alternative micro LED mass transfer technology: self-assembly, in: 2022 23rd International Conference on Electronic Packaging Technology (ICEPT), IEEE,, 2022, pp. 1–5, https://doi.org/10.1109/ICEPT56209.2022.9873296.
[361] Y. Wu, J. Ma, P. Su, L. Zhang, B. Xia, Full-color realization of micro-LED displays, Nanomaterials 10 (2020) 2482, https://doi.org/10.3390/nano10122482.
[362] Z. Bi, Z. Chen, F. Danesh, L. Samuelson, From nanoLEDs to the realization of RGB-emitting microLEDs, in: 2021: pp. 223–251. https://doi.org/10.1016/bs.semsem.2021.01.001.
[363] W. Li, Z. Zhang, Y. Cheng, W. Zhou, P-8.4: research on chip layout design and printing process optimization of mini-LED light board, SID Symp. . Dig. Tech. Pap. 54 (2023) 760–762, https://doi.org/10.1002/sdtp.16404.
[364] F. Gou, E.-L. Hsiang, G. Tan, Y.-F. Lan, C.-Y. Tsai, S.-T. Wu, Tripling the optical efficiency of color-converted micro-LED displays with funnel-tube array, Cryst. (Basel) 9 (2019) 39, https://doi.org/10.3390/cryst9010039.
[365] S.H. Kang, S. Mhin, H. Han, K.M. Kim, J.L. Jones, J.H. Ryu, J.S. Kang, S.H. Kim, K. B. Shim, Ultrafast method for selective design of graphene quantum dots with highly efficient blue emission, Sci. Rep. 6 (2016) 38423, https://doi.org/10.1038/srep38423.
[366] P. Li, H. Li, H. Zhang, Y. Yang, M.S. Wong, C. Lynsky, M. Iza, M.J. Gordon, J. S. Speck, S. Nakamura, S.P. Denbaars, Red InGaN micro-light-emitting diodes (> 620 nm) with a peak external quantum efficiency of 4.5% using an epitaxial tunnel junction contact, Appl. Phys. Lett. 120 (2022). ⟨https://doi.org/10.1063/5.0086912⟩.
[367] B. Pezeshki, R. Kalman, A. Tselikov, C. Danesh, High speed light microLEDs for visible wavelength data communication, in: 2021. https://doi.org/10.1117/12.2585000.
[368] N. Bamiedakis, X. Li, J.J.D. McKendry, E. Xie, R. Ferreira, E. Gu, M.D. Dawson, R. V. Penty, I.H. White, Micro-LED-based guided-wave optical links for visible light communications, : Int. Conf. Transparent Opt. Netw. (2015), https://doi.org/10.1109/ICTON.2015.7193686.
[369] H. Ding, G. Lv, Z. Shi, D. Cheng, Y. Xie, Y. Huang, L. Yin, J. Yang, Y. Wang, X. Sheng, Optoelectronic sensing of biophysical and biochemical signals based on photon recycling of a micro-LED, Nano Res 14 (2021), https://doi.org/10.1007/s12274-020-3254-2.
[370] H. Xu, J. Zhang, K.M. Davitt, Y.K. Song, A.V. Nurmikko, Application of blue-green and ultraviolet micro-LEDs to biological imaging and detection, J. Phys. D. Appl. Phys. 41 (2008), https://doi.org/10.1088/0022-3727/41/9/094013.
[371] A. Pandey, Y. Xiao, M. Reddeppa, Y. Malhotra, J. Liu, J. Min, Y. Wu, Z. Mi, A red-emitting micrometer scale LED with external quantum efficiency >8%, Appl. Phys. Lett. 122 (2023). ⟨https://doi.org/10.1063/5.0129234⟩.
[372] A. Gudimalla, R.K. Mishra, P. Arora, Novel approaches to nanomedicine and nanotechnology, 2017.
[373] S.M. Sadaf, Y.H. Ra, T. Szkopek, Z. Mi, Monolithically integrated metal/semiconductor tunnel junction nanowire light-emitting diodes, Nano Lett. 16 (2016), https://doi.org/10.1021/acs.nanolett.5b04215.
[374] S.M. Sadaf, Y.H. Ra, H.P.T. Nguyen, M. Djavid, Z. Mi, Alternating-current InGaN/GaN tunnel junction nanowire white-light emitting diodes, Nano Lett. 15 (2015), https://doi.org/10.1021/acs.nanolett.5b02515.
[375] R.K. Mishra, D. Li, I. Chianella, S. Goel, S. Lotfian, H. Yazdani Nezhad, Low electric field induction in BaTiO3-epoxy nanocomposites, Funct. Compos. Mater. 4 (2023) 6, https://doi.org/10.1186/s42252-023-00043-1.
[376] N. Sanders, D. Bayerl, G. Shi, K.A. Mengle, E. Kioupakis, Electronic and optical properties of two-dimensional GaN from first-principles, Nano Lett. 17 (2017), https://doi.org/10.1021/acs.nanolett.7b03003.
[377] I.A. Navid, A. Pandey, Y.M. Goh, J. Schwartz, R. Hovden, Z. Mi, GaN-based deep-nano structures: break the efficiency bottleneck of conventional nanoscale optoelectronics, Adv. Opt. Mater. 10 (2022), https://doi.org/10.1002/adom.202102263.
[378] L. Zhang, J.J. Shi, Influence of surface optical phonons on exciton binding energies of a quasi-one-dimensional wurtzite GaN-based nanowire: Quantum size effect, J. Appl. Phys. 113 (2013), https://doi.org/10.1063/1.4794527.