

Recent advances of flexible GaN-based devices and chips

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Abstract:

GaN-based optoelectronics have developed rapidly and emerged as key pillars in advanced optoelectronics. However, the inherent rigidity of conventional epitaxial substrates imposes fundamental limitations on mechanical flexibility, hindering their deployment in next-generation wearable and bio-integrated systems. This review provides a comprehensive overview of the emerging field of flexible GaN-based optoelectronics, spanning from epitaxial innovation to system-level integration. It begins by discussing the paradigm shift from conventional three-dimensional bonding to van der Waals epitaxy utilizing two-dimensional (2D) materials. These 2D platforms not only mitigate lattice mismatch strain and facilitate mechanical exfoliation via weak interfacial forces, but also enable substrate recycling and the realization of freestanding single-crystalline membranes. Subsequently, this review summarizes the device physics and flexible implementations of key functional units, including micro-light-emitting devices, high-sensitivity photodetectors, laser diodes and emerging neuromorphic synaptic devices. Particular attention is devoted to the pivotal role of transfer and integration technologies (*e.g.*, laser lift-off, transfer printing and fluidic self-assembly) that bridge the gap between high-performance rigid epitaxy and wearable chips. By elucidating the connections between material growth, device physics and integration strategies, this review highlights future opportunities for the development of high-performance, intelligent and flexible GaN-based systems. The overview of applications is summarized from flexible displays and biomedical devices to brain–computer interfaces and neuromorphic systems. These examples demonstrate the transformative potential of flexible GaN-based technology and outline the critical steps toward commercialization and clinical translation. Therefore, flexible GaN-based devices and chips have great promising application prospects, which can significantly mitigate the current challenges and promote the development of mechanically adaptable intelligent systems and human civilization.

Keywords: Flexible semiconductor, gallium nitride, micro-LED, integrated technology, neuromorphic device, multifunctional chip

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1. Introduction

Gallium nitride (GaN) and its III-nitride alloys have revolutionized modern optoelectronics and high-power electronics, underpinning technologies ranging from energy-efficient solid-state lighting and Blu-ray storage to 5G communication infrastructure¹. The success of these devices is largely attributed to the superior material properties of GaN, including its direct and tunable bandgap, high breakdown field, and exceptional thermal stability. Yet, the vast majority of commercial GaN devices are manufactured on rigid, single-crystalline substrates such as sapphire, silicon carbide (SiC) and silicon (Si)². This rigid form factor, dictated by the requirements of high-temperature epitaxial growth and lattice matching, is inherently at odds with the emerging technological frontier of flexible, stretchable and wearable electronics³.

The pursuit of mechanical flexibility in high-performance semiconductors is driven by the demand for seamless human-machine interfaces, conformable biomedical sensors, lightweight and portable display systems⁴, *etc.* While organic semiconductors and amorphous oxides offer intrinsic flexibility, they often fall short in terms of carrier mobility, radiative efficiency, and long-term environmental stability compared to crystalline inorganic materials like GaN. Consequently, the challenge is not to replace GaN, but to liberate it from its rigid substrate. This endeavor necessitates a fundamental rethinking and redesigning of epitaxial growth, device architecture and system assembly.

Early efforts to realize flexible GaN devices primarily relied on substrate thinning or the transfer of fabricated device layers using laser lift-off (LLO). While effective, these post-growth processes can introduce mechanical damage, thermal stress, and are often wasteful, as the expensive native substrate is sacrificed. This has spurred two interconnected research directions that form the core of this review. The first direction focuses on epitaxial innovation at the interface. The emergence of van der Waals

epitaxy (vdWE) on two-dimensional (2D) materials, specifically graphene, hexagonal boron nitride (h-BN) and transition metal dichalcogenides (TMDs), represents a fundamental shift in growth mechanics^{5,6}. As detailed in Section 2, the weak out-of-plane van der Waals (vdW) forces at these 2D/GaN interfaces act as a natural release layer⁷. This approach paves the way for substrate recycling and the direct integration of high-performance III-nitride films onto arbitrary flexible carriers. The second direction is the maturation of heterogeneous integration and mass transfer technologies. Liberated GaN membranes and microscale devices must be precisely assembled onto flexible backplanes to form functional systems. Section 4 and 5 explore the technological arsenal enabling this transition, from high-throughput laser-induced forward transfer (LIFT) and elastomeric stamp printing to fluidic self-assembly. These techniques are the enablers of advanced displays and multifunctional sensor arrays, allowing the monolithic integration of GaN optoelectronics with Si-based or oxide-based thin-film transistor (TFT) driving circuits on pliable substrates^{8–10}.

Beyond mere mechanical flexibility, the integration of GaN with flexible platforms unlocks new device physics and functionalities. As discussed in Section 3, the synergy between piezoelectric polarization in GaN and mechanical strain gives rise to piezotronic and piezo-phototronic effects, enabling self-powered sensors and strain-tunable photodetectors. Furthermore, the persistent photoconductivity (PPC) and charge trapping dynamics inherent to GaN heterostructures are being actively exploited to emulate synaptic plasticity in neuromorphic computing (Section 3 and 4). Flexible GaN-based synaptic transistors and artificial vision systems are emerging as promising candidates for low-power and brain-inspired edge computing architectures^{11,12}.

Despite remarkable progress, the field of flexible GaN optoelectronics stands at a critical juncture where fundamental research must converge with scalable manufacturing. Challenges pertaining to thermal management in deformed states, long-term mechanical fatigue under cyclic strain, and the yield of high-density microscale

transfers remain open research questions. This review aims to provide a systematic and critical synthesis of the state-of-the-art in flexible GaN technology. We trace the lifecycle of a flexible GaN device, from its birth in novel 2D-assisted epitaxy to its functional deployment in integrated sensing, display and neuromorphic systems. Fig. 1.1 illustrates the key technological milestones and emerging application scenarios, which serves as a representative example of GaN-based optoelectronics. It charts the evolution from epitaxial growth and chip fabrication to mass transfer and heterogeneous integration, culminating in diverse flexible applications. The classification and icons highlight the convergence of materials innovation, device engineering and system-level assembly that defines the field of flexible GaN-based devices. By elucidating the connections between material growth, device physics and integration strategies, this review highlights future opportunities for the development of high-performance, intelligent and mechanically imperceptible GaN-based systems. The comprehensive overview of applications is summarized in Section 6, ranging from flexible displays and biomedical devices to brain–computer interfaces and neuromorphic systems. These examples demonstrate the transformative potential of flexible GaN technology and outline the critical steps toward commercialization and clinical translation.

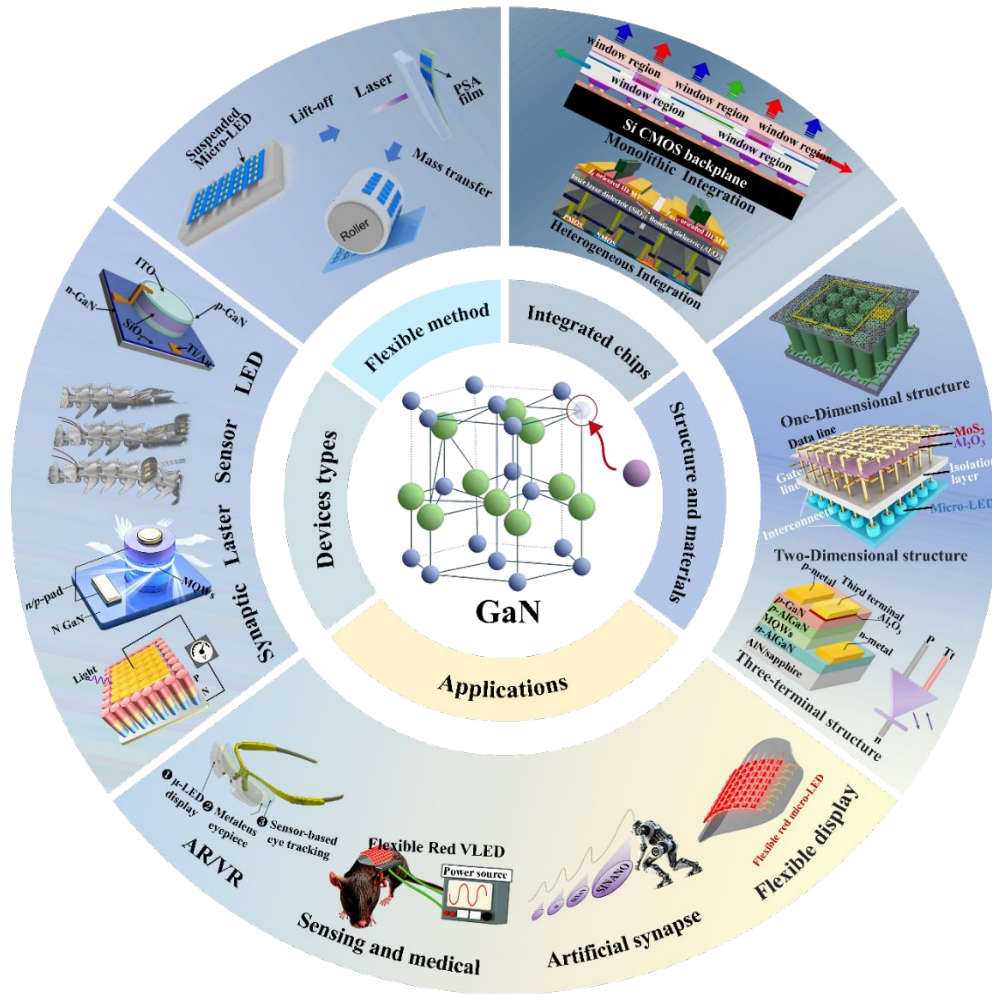


Fig. 1.1 Schematic overview of GaN-based technology development and applications^{13–29}. Copyright © 2021, Springer Nature. Copyright © 2026, The American Association for the Advancement of Science. Copyright © 2026, Springer Nature. Copyright © 2022, Springer Nature. Copyright © 2021, Society for Information Display. Copyright© 2020, The Society for Information Display. Copyright © 2024 ,Wiley. Copyright © 2018, American Chemical Society. Copyright © 2021, Springer Nature. Copyright © 2025, Springer Nature. Copyright © 2024, Springer Nature. Copyright © 2023, IOP. Copyright © 2025, Springer Nature. Copyright © 2025, Society for Information Display. Copyright © 2023 Springer Nature. Copyright © 2022, American Chemical Society. Copyright © 2024, Optica Publishing Group.

2. Materials and Structures

The realization of mechanically compliant GaN-based devices begins with a strategic epitaxial platform. This section charts the material systems that have redefined the boundaries between rigidity and flexibility. We first assess the capabilities and inherent limitations of conventional heterogeneous substrates (sapphire, Si and SiC), whose lattice and thermal expansion mismatches with GaN demand increasingly sophisticated buffer layer and strain mitigation strategies. Building on these foundations, we then discuss the transformative role of 2D materials, where the transition from strong covalent bonding to weak vdW interactions enables damage-free epilayer release, substrate recycling and a pathway toward truly freestanding single-crystalline membranes. The discussion subsequently turns to one-dimensional GaN nanostructures, whose unique geometrical morphology and superior strain accommodation circumvent many of the mechanical constraints of planar films while simultaneously opening new avenues for multifunctional integration. Collectively, these material platforms constitute the essential building blocks from which flexible GaN devices are subsequently constructed.

2.1 Epitaxial Substrates

The selection of epitaxial substrates and the optimization of epitaxial technologies are crucial for GaN-based display devices³⁰. The properties of substrates directly determine the crystal quality, defect density and surface flatness of epitaxial wafers, while high-quality epitaxial wafers serve as the core prerequisite for the realization of flexible display devices. The stringent requirements for the yield and uniformity in high-resolution arrays, coupled with the significant impact of defect-induced non-radiative recombination on light output efficiency, pose substantial challenges to the compatibility of substrate materials and the stability of epitaxial processes. Hence, the substrate materials and epitaxial technologies are crucial for advancing the

technological progress and commercialization of flexible GaN-based devices and chips.

Currently, mainstream heterogeneous substrates include sapphire, Si, and SiC^{31–35}, each with distinct core properties and application characteristics (Table 1). Among these, sapphire is the most mature substrate material for GaN epitaxial growth, which are typically available in sizes of 4 inches or larger³⁶. Due to its high mechanical stability, strong chemical inertness and excellent high-temperature resistance³⁴, sapphire remains widely used in light-emitting diodes (LEDs) and micro-LED devices. However, sapphire exhibits a lattice mismatch of ~13.8% with GaN, along with significant differences in thermal expansion coefficients, which easily lead to high-density dislocations and residual stress in the epitaxial layer, directly impairing the optoelectronic performance and reliability of devices³⁷. To mitigate this issue, researchers have developed various optimization technologies, such as introducing GaN or AlN buffer layers, adopting patterned sapphire substrates (PSS), and implementing lateral epitaxial over-growth (LEO), to reduce dislocation density³⁶. Among these approaches, PSS has been particularly effective in modulating nucleation behavior and dislocation evolution through surface patterning. For instance, GaN growth on cone-PSS and dome-PSS exhibits distinct nucleation and coalescence behaviors compared to flat sapphire substrates (Fig. 2.1a and 2.1b)³⁸. It has been shown that increasing the nucleation time (*e.g.*, from 40 s to 160 s) significantly improves GaN growth quality on patterned substrates, whereas limited improvement is observed on flat sapphire. In particular, dome-PSS demonstrates superior epitaxial performance compared to cone-PSS. This can be attributed to the geometry of dome-shaped patterns, which provide smoother curvature and facilitate more frequent nucleation events along trench regions, thereby promoting lateral overgrowth and improving film coalescence. As a result, GaN films grown on dome-PSS exhibit enhanced surface morphology and reduced X-ray diffraction (XRD) full width at half maximum (FWHM), indicating improved crystalline quality. Strain analysis further reveals that although GaN layers grown on dome-PSS initially exhibit higher in-plane residual strain due to enhanced

lateral overgrowth, the strain gradually relaxes with increasing nucleation time. In contrast, GaN films grown on flat sapphire substrates generally exhibit relatively higher intrinsic crystalline quality in the absence of pattern-induced growth perturbations. However, they suffer from larger accumulated strain due to the lack of effective strain relaxation pathways. Overall, while these strategies can effectively reduce dislocation density and improve surface morphology, the threading dislocation density in GaN films on sapphire substrates typically remains on the order of 10^9 – 10^{10} cm⁻², indicating the inherent limitations of conventional heteroepitaxy on rigid substrates³⁸.

Table 1. Comparison of epitaxial substrates^{2,32,36,37,39–42}.

Substrate	Lattice mismatch	Thermal conductivity	Cost	Wafer size	Defect density	Key advantages	Limitations
Sapphire	~13.8%	Low (~60 W/m·K)	Low	Medium (4–6 inch)	High (10^9 – 10^{10} cm ⁻²)	Mature technology, stable	High defect density
Si	~17%	Medium (~150 W/m·K)	Very low	Large (>200 mm)	Medium	Low cost, large-scale integration	Cracking, stress issues
SiC	~3.5%	High (~370 W/m·K)	High	Limited (4–6 inch)	Low	Excellent thermal performance	Expensive, small size

In addition, Si substrates have emerged as an important research direction for GaN epitaxy due to their availability in large sizes, cost advantages and good thermal conductivity⁴³. GaN-on-Si epitaxial wafers offer potential cost benefits and manufacturing feasibility for LEDs⁴⁴. However, the lattice mismatch between GaN and Si is as high as 17%, and the thermal expansion coefficient of GaN is approximately twice that of Si⁴². During the cooling process from the growth temperature (exceeding 1000°C) to room temperature, enormous thermal stress easily causes cracking of the epitaxial layer. Meanwhile, chemical reactions may occur at the GaN-Si interface

during dry etching for device unit definition, further increasing process complexity⁴⁴. To address these challenges, researchers have improved epitaxial quality through strain engineering and buffer layer optimization (Fig. 2.1c). Optical microscopy characterization (Fig. 2.1d) reveals that both nitridation temperature and buffer structure critically influence crack formation in GaN films. Specifically, high-temperature nitridation at 900 °C leads to the formation of amorphous Si_3N_4 islands on the Si surface, which subsequently induce inversion domains in the AlN nucleation layer and introduce additional tensile stress, resulting in crack formation regardless of the buffer configuration employed⁴⁵. In contrast, low-temperature nitridation at 700 °C produces a uniform crystalline SiN interfacial layer that effectively suppresses amorphous phase formation. When combined with either the Provence structure or step-graded (Al,Ga)N buffers⁴⁵, crack-free GaN epitaxy can be achieved. Among these, the step-graded (Al,Ga)N buffer exhibits the most favorable performance, yielding GaN films with FWHM values as low as 648 arcsec for the (0002) plane and 551 arcsec for the (10–15) plane. Furthermore, the residual biaxial tensile stress is reduced to approximately 0.63 GPa at room temperature, indicating significantly improved crystal quality and strain relaxation compared to those of alternating GaN/AlN structure⁴⁶.

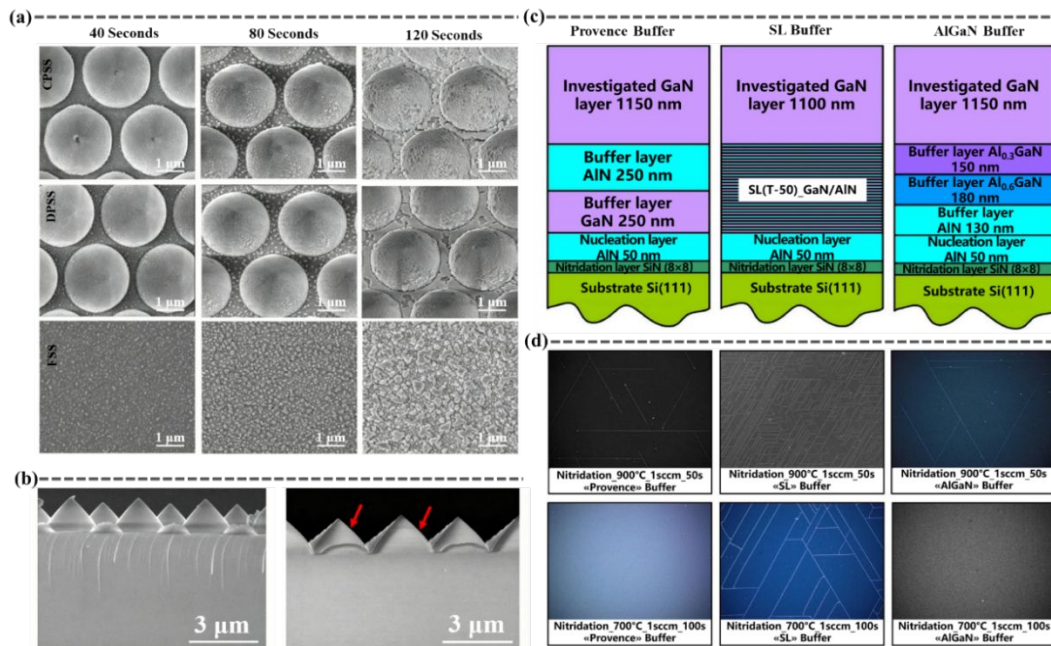


Fig. 2.1 (a) SEM images of GaN growth on flat sapphire, cone-PSS and dome-DPSS. (b) Cross-sectional morphology illustrating the geometric features of PSS.³⁸ Copyright

© 2021, Elsevier. (c) Schematic diagrams of representative buffer layer structures on Si substrates, including Provence, superlattice and step-graded (Al,Ga)N buffers. (d) Optical microscopy images showing crack formation under different nitridation temperatures and buffer configurations.⁴⁵ Copyright © 2024, Elsevier.

Owing to its high thermal conductivity, electrical conductivity and relatively small lattice mismatch with GaN, SiC is widely regarded as one of the most favorable substrate materials for high-power and high-frequency GaN-based devices. Compared with sapphire and Si, SiC offers superior thermal management capability (Table 1), which is critical for maintaining device stability and reliability under high power density operation^{31,33–36}.

Nevertheless, a lattice mismatch of ~3.5% still exists between GaN and SiC. Although significantly smaller than those of sapphire and Si, this mismatch can still lead to defect accumulation during large-area epitaxial growth. Moreover, the high cost of SiC substrates and their limited scalability in wafer size remain major constraints for their application in large-area display technologies.

From an epitaxial perspective, GaN growth on SiC similarly relies on buffer layer engineering and strain management strategies to further improve crystalline quality. As a result, SiC-based GaN heterostructures have been extensively employed in high-frequency electronic devices and high-brightness optoelectronic applications, where thermal dissipation and material quality are of paramount importance⁴⁷.

2.2 Two-Dimensional Materials for GaN Integration

While traditional rigid substrates (*e.g.*, sapphire, Si and SiC) have catalyzed the rapid evolution of GaN-based technologies, they impose fundamental constraints on flexible device integration. As discussed previously, inherent limitations such as lattice

mismatch, thermal stress and the complexities associated with epitaxial layer delamination remain significant hurdles. In this context, two-dimensional (2D) materials have emerged as a promising epitaxial platform. By leveraging vdW interactions rather than conventional strong covalent bonding, 2D materials offer a new material system and growth mechanism⁴⁸. Distinct from traditional heteroepitaxy, van der Waals epitaxy (vdWE) enables the growth of high-quality GaN films without the stringent requirement for lattice matching. The weak interfacial interaction between the 2D template and the epitaxial layer effectively suppresses strain accumulation and dislocation propagation. This not only enhances crystalline quality but also provides a natural advantage for subsequent mechanical exfoliation and transfer.

Among the diverse library of 2D materials, graphene, hexagonal boron nitride (h-BN) and transition metal dichalcogenides (TMDs) are the most extensively researched systems for GaN epitaxy. Graphene is widely utilized as a template for vdWE due to its exceptional thermal stability, atomically smooth surface and high carrier mobility. However, its lack of dangling bonds and low surface energy significantly suppress the nucleation of GaN, often leading to three-dimensional (3D) island or cluster growth rather than large-area continuous single-crystal films in early studies⁴⁹. To overcome this, researchers initially introduced buffer layers (AlN or h-BN) to promote nucleation. Despite these efforts, the epitaxial quality remained inferior to that on sapphire or SiC, indicating a fundamental divergence between vdW mechanisms and traditional 3D covalent epitaxy.

Consequently, developing novel epitaxial strategies for 2D interfaces has become critical. Recently, direct vdWE on epitaxial graphene/SiC systems has achieved significant breakthroughs. By precisely tuning growth kinetics—such as through a two-step method involving low-temperature nucleation followed by high-temperature growth—high-quality single-crystal GaN films can be realized without a buffer layer. Despite a ~23% lattice mismatch between graphene and GaN, and surface roughness

of ~ 3 Å, approaching the quality of conventional rigid-substrate systems⁶. Fig. 2.2a illustrates a schematic for the growth and transfer of single-crystal films on epitaxial graphene. Beyond high crystalline quality, this system inherently possesses superior transferability, which is vital for flexible electronics. Since the GaN-graphene interface is maintained only by weak vdW forces, the epitaxial film can be exfoliated without damage and transferred to arbitrary targets, such as polymers or flexible substrates. This process circumvents the thermal damage and defect introduction inherent in conventional laser lift-off (LLO) techniques, significantly enhancing device reliability and yield. Furthermore, the exfoliated graphene/SiC substrate remains virtually residue-free and can be reused for subsequent growth cycles. This growth-exfoliation-regrowth capability not only reduces manufacturing costs but also provides a viable path for large-scale flexible device production. GaN-based light-emitting devices (LEDs) fabricated via this method maintain stable performance after transfer (Fig. 2.2b)⁶.

In comparison to graphene, h-BN is a structural analog with distinct advantages for GaN vdWE, including a wide bandgap (~ 5.9 eV) and superior chemical and thermal stability⁵⁰. In high-temperature epitaxial environments, h-BN is more resistant to structural degradation or interfacial reactions than graphene, which helps maintain interfacial stability and epitaxial consistency. However, similar to graphene, the lack of dangling bonds on the h-BN surface leads to weak GaN nucleation and a tendency toward 3D island growth. Current research largely relies on buffer layer engineering (AlN interlayers) to facilitate continuous film growth. While GaN epitaxy on AlN/h-BN heterostructures has been demonstrated, the crystalline quality remains limited, with dislocation densities typically in the order of significantly higher than those found in sapphire-based systems. Further studies indicate that the differences in epitaxial behavior between h-BN and graphene stem not only from surface energy, but also from interfacial stability. In high-temperature ammonia environments, graphene may undergo etching or reconstruction, whereas h-BN exhibits superior corrosion resistance

due to the high bond energy of B–N. Thus, h-BN is more conducive to maintaining interfacial integrity during prolonged or high-temperature growth. Nevertheless, a key challenge for the h-BN system remains: increasing nucleation density and epitaxial continuity without sacrificing interfacial stability. Additionally, due to its insulating nature, h-BN may restrict vertical carrier transport, a factor that must be considered when designing vertical devices or three-terminal structures.

Beyond graphene and h-BN, TMDs such as molybdenum disulfide (MoS_2) have been widely explored as 2D platforms for GaN epitaxy and integration. Unlike its counterparts, MoS_2 is a semiconductor with a direct bandgap (~ 1.8 eV for a monolayer), allowing it to function not only as an epitaxial buffer but also as an active functional component within the device⁵¹. At the epitaxial level, MoS_2 utilizes vdW interactions to form a weak interfacial coupling with GaN, thereby mitigating strain accumulation from lattice mismatch. For instance, Takuya Kadowaki *et al.* fabricated a van der Waals heterojunction uni-travelling-carrier photodiode (UTC-PD) employing two-dimensional transition-metal dichalcogenide molybdenum disulfide (MoS_2) as the photo-absorption layer and a gallium nitride (GaN) thin film as the carrier collection layer. Figure 2.2(c) presents the energy band diagram of the MoS_2 /GaN heterojunction. The rapid vertical carrier transport across the heterointerface is facilitated by the direct epitaxial growth of MoS_2 on the GaN thin film. The resulting device exhibits a frequency response in the gigahertz regime and a quantum efficiency of approximately 1% across the visible spectrum, highlighting the potential of this approach for high-speed visible-light optoelectronics⁵.

More importantly, MoS_2 can form various heterojunctions with GaN (*e.g.*, vertical or lateral integration), enabling novel device functionalities. In photodetectors, MoS_2 can serve as a carrier transport or modulation layer to enhance photo-response and sensitivity. In flexible electronics, its mechanical flexibility and semiconducting properties allow for the construction of high-performance integrated heterostructures⁵.

The band alignment between MoS₂ and GaN also opens design space for low-power devices and novel three-terminal structures. The core advantage of MoS₂ lies in its semiconducting functionality, allowing it to transition from an epitaxial template to a functional device unit. For example, MoS₂ thin-film transistor (TFT) arrays can serve as active-matrix driving backplanes for GaN micro-LED pixels, providing precise addressing and control while maintaining mechanical flexibility (Fig. 2.2d and 2.2e). Compared to conventional amorphous Si or oxide semiconductor TFTs, MoS₂ devices exhibit superior performance in suppressing short-channel effects and maintaining electrical stability under bending. This complementary functional system shows immense potential for flexible displays, wearable sensors and neuromorphic computing systems²⁴. Hence, MoS₂ represents a critical pathway for achieving highly integrated, flexible GaN-based electronic and optoelectronic systems.

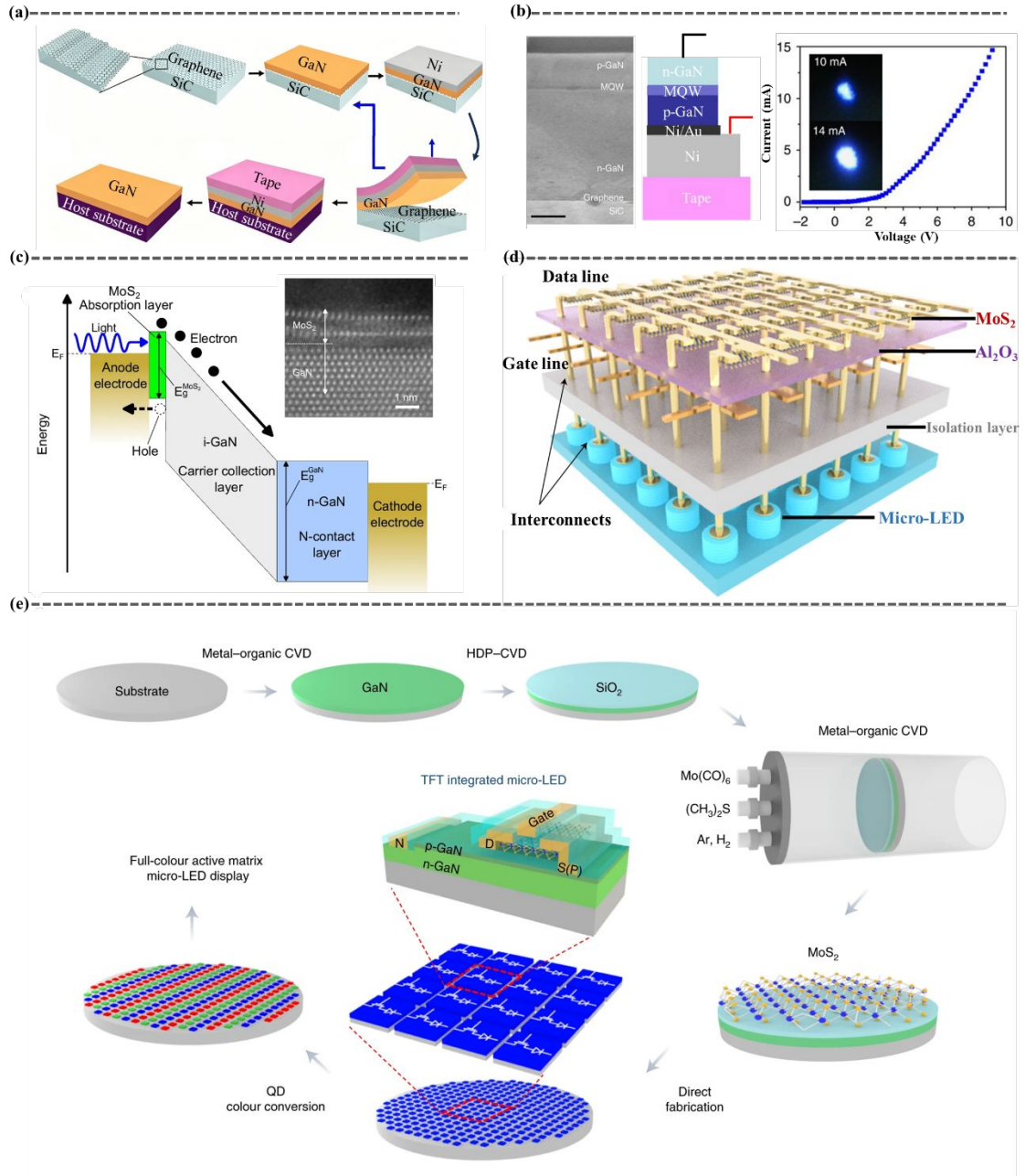


Fig. 2.2 (a) Schematic of a method for growing/transferring single-crystalline thin films on/from epitaxial graphene. (b) Cross-sectional TEM image of LED stacks on a graphene/SiC substrate and schematic of a transferred visible LED device on the tape and I-V characteristic of a transferred LED.⁶ Copyright © 2014, Springer Nature. (c) Band structure of a MoS₂/GaN UTC-PD.⁵ Copyright © 2025, Springer Nature. (d) Schematic illustration of the micro-LED display.²⁴ Copyright © 2021, Springer Nature. (e) Schematic illustration of the monolithic integration process.⁵² Copyright © 2022, Springer Nature.

2.3 One-Dimensional GaN Nanostructures

Owing to the synergistic effects of their unique geometrical morphology and wide-bandgap semiconductor properties, one-dimensional (1D) GaN-based nanowires not only provide a way to overcome the physical limitations of conventional bulk and thin-film architectures in flexible integration, but also provide an efficient charge modulation platform for neuromorphic computing⁵³. The intrinsic flexibility of GaN nanowires originates from a dual regulation mechanism of “structural decoupling” and “lattice tolerance”, which renders them superior to thin-film devices based on strain-relief layers or thinning processes in terms of deformation stability. The high aspect ratio of 1D structures endows GaN nanowires with excellent strain accommodation capability. Unlike bulk thin films, where stress concentration and threading dislocations readily occur at heteroepitaxial interfaces, nanowires dissipate mechanical energy through an “individual deformation–collective coordination” mechanism. Individual nanowires can accommodate strain energy via large-angle tilting or elastic bending, while nanoscale inter-wire spacing provides sufficient mechanical buffering.

As shown in Fig. 2.3a, Min Jiang *et al.* employed molecular beam epitaxy (MBE) combined with electrochemical lift-off to achieve damage-free transfer of (Al,Ga)N/GaN nanowires from the original Si substrate to flexible ITO/glass substrates. Nicholas R. Glavin *et al.* demonstrated that GaN nanocolumns transferred onto flexible substrates could maintain stable microwave transmission performance under tensile strains up to 20%⁵⁴. In terms of fabrication, advanced lift-off techniques are crucial for preserving structural integrity. In addition, the wurtzite crystal structure of GaN exhibits favorable atomic-layer slip characteristics along the c-axis. Xin Tang *et al.* observed via high-resolution STEM that even under extreme tensile strain exceeding 30%⁵⁵, nanowires maintained continuous and well-defined lattice fringes without significant defect proliferation, further validating their potential as ultra-flexible electronic building cornerstones.

The controllable synthesis of GaN nanowires enables their integration with 2D materials and quantum dots (QDs), forming hybrid heterostructures for monolithic sensing–computing integration. By precisely engineering carrier dynamics at interfaces, researchers have developed multifunctional devices that combine high-sensitivity photodetection with neuromorphic synaptic behavior. In synaptic emulation, nanowire-based heterostructures exploit interfacial trap states to mimic synaptic weight modulation. As illustrated in Fig. 2.3b, Yukun Zhao *et al.* constructed an (Al,Ga)N nanowire/graphene heterojunction device with defect states in graphene and oxygen vacancies on nanowire surfaces forming hybrid recombination centers, enabling the emulation of paired-pulse facilitation (PPF) behavior. Operating at ultra-low bias, the energy consumption per synaptic event is reduced to 2.6 μJ .

To further expand functionality, Zhixiang Gao *et al.* introduced a quantum dot–nanowire (QD-NW) architecture. As shown in Fig. 2.3c, the system utilizes the quantum-confined Stark effect (QCSE) to dynamically regulate carrier recombination probability. Under different bias polarities, the device exhibits markedly distinct relaxation dynamics: negative bias induces long-term photocurrent relaxation ($\tau_2 = 32.57$ s), whereas positive bias results in short-term response ($\tau_2 = 1.46$ s). This bias-tunable dynamic behavior provides a physical basis for constructing flexible neuromorphic devices with sense–compute integration capability. Leveraging the excellent synaptic plasticity of GaN nanowires, efficient pattern recognition has been demonstrated at the algorithmic level. Devices fabricated by Yukun Zhao *et al.* exhibit pronounced short-term memory (STM) characteristics, with PPF indices following a double-exponential decay behavior. In contrast, devices reported by Zhixiang Gao *et al.* achieve a transition from STM to long-term memory (LTM) through optical intensity modulation. In neural network simulations, multilayer perceptron (MLP) models constructed based on such LTP/LTD behaviors achieved a recognition accuracy of 92% on the Modified National Institute of Standards and Technology (MNIST)

handwritten digit dataset⁵⁶.

Moreover, GaN nanowire artificial synapses have been applied in bio-inspired vision systems. The dual-mode devices can switch between photodetection and synaptic operation modes¹². When integrated into humanoid robotic platforms, they enable learning of incident light direction and subsequent motion execution. More advanced visual chips further emulate the parvocellular (Parvo, image enhancement) and magnocellular (Magno, motion detection) pathways of the human retina, maintaining over 90% recognition robustness under complex noisy environments. This architecture effectively alleviates the data transfer bottleneck between sensing and processing units, providing a promising solution for autonomous robotics and low-power vision systems.

Despite their significant potential, practical implementation of GaN nanowire arrays still faces critical challenges. First, scalability and uniformity remain major concerns, as the high cost of MBE growth techniques and statistical variations in device parameters (*e.g.*, a coefficient of variation of $\sim 12\%$ in relaxation time τ_2) hinder large-scale integration. Second, interfacial stability issues persist: under cyclic mechanical stress, increases in contact resistance and oxygen-vacancy-induced drift of synaptic weights remain unresolved and require advanced encapsulation strategies. Future research should focus on the development of standardized transfer processes and high-density integration technologies to enable ultrahigh-performance flexible neuromorphic chips.

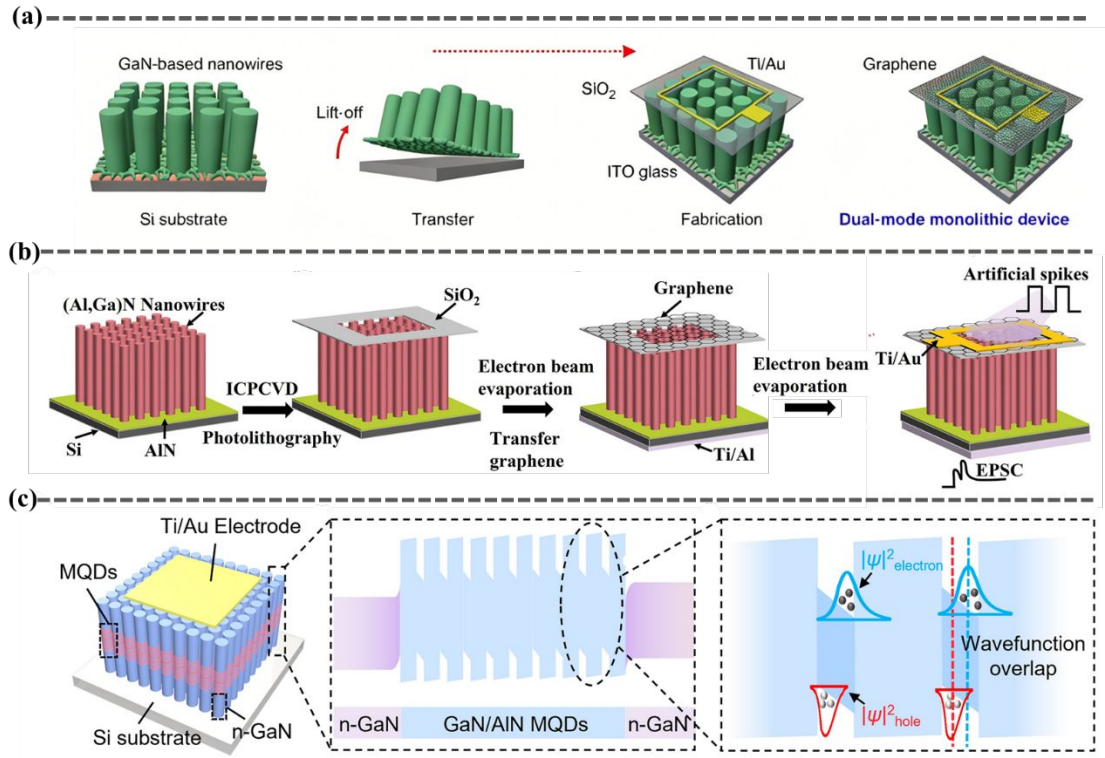


Fig. 2.3 (a) Schematic illustrations of the fabricated processes for the dual-mode monolithic device.¹⁶ Copyright © 2025, Springer Nature. (b) Schematic illustrations of the fabricated processes for synaptic device.⁵⁶ Copyright © 2023, AIP Publishing. (c) Schematic of the vertically structured optoelectronic device based on the designed nanowires.⁵⁷ Copyright © 2025, Springer Nature.

3. Device Classification

With the material platforms established, the focus shifts to the functional units that convert GaN intrinsic physical properties into optoelectronic action. As overviewed in Fig. 3.1, the devices relevant to flexible systems can be broadly subdivided according to their primary operational principle. Light-emitting devices (LEDs) exploit radiative carrier recombination for high-brightness, energy-efficient displays. By contrast, photodetectors and sensors transduce optical, chemical or mechanical stimuli into electrical signals, leveraging the wide bandgap and strong polarization fields of III-nitrides. Laser diodes require careful optical cavity design to achieve stimulated emission, delivering coherent light sources for communication and sensing. More recently, synaptic devices have emerged as a distinct category, purposefully harnessing persistent photoconductivity and interfacial charge trapping to emulate the plasticity of biological synapses for neuromorphic computing. This functional taxonomy structures the following subsections and highlights the versatility of GaN-based heterostructures in serving as a unified platform for both conventional and intelligent optoelectronic systems.

As illustrated by the energy-band schematics in Fig. 3.1, these four device types are different manifestations of the same physical framework: carrier injection, transport, trapping and recombination. Their functional differences arise from how these processes are biased, optically excited or cavity-confined. In a LED, forward bias injects electrons and holes into (In,Ga)N/GaN multiple quantum wells (MQWs), where they recombine radiatively to produce spontaneous emission. The emission wavelength is determined by the quantum-confined Stark effect (QCSE) and the indium composition⁵⁸. A photodetector operates under zero or reverse bias. Illumination by an external light source generates electron-hole pairs, which are separated by the built-in or applied electric field to produce a photocurrent. The strong polarization fields at (Al,Ga)N/GaN heterointerfaces induce a two-dimensional electron gas (2DEG) that

provides internal gain, enhancing weak-signal detection⁵⁸. A laser diode requires higher current injection to achieve population inversion. When the injection current exceeds threshold, stimulated emission dominates. At the band level, forward bias shifts the quasi-Fermi levels into the quantum well region, establishing population inversion. Artificial synaptic devices exploit interface defect states or deep-level traps in GaN heterostructures^{59,60}. Under optical or electrical stimulation, photogenerated carriers are captured by these traps, causing persistent photoconductivity. After stimulation ceases, trapped carriers are slowly released, generating a sustained excitatory postsynaptic current. By adjusting the intensity, number, or frequency of stimulation pulses, a gradual transition from short-term plasticity to long-term potentiation can be achieved, mimicking biological learning and memory. These unified view highlights the versatility of GaN heterostructures as a platform bridging conventional optoelectronics and neuromorphic computing^{11,12,61}.

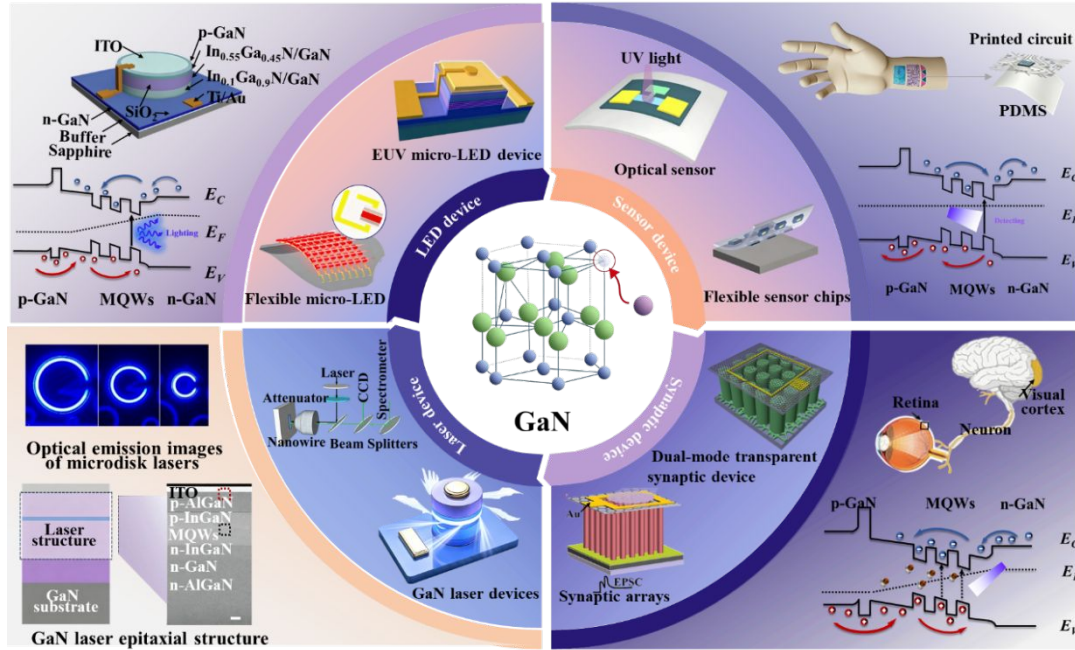


Fig. 3.1 Schematic overview of device types^{14,19,25,27,59,62–66}. Copyright © 2026, Springer Nature. Copyright © 2023, AIP Publishing. Copyright © 2025, Springer Nature. Copyright © 2026, American Chemical Society. Copyright © 2024, Wiley. Copyright © 2026, The American Association for the Advancement of Science. Copyright © 2024, Springer Nature. Copyright © 2025, Springer Nature. Copyright © 2024, Optica Publishing Group.

3.1 Light-emitting Devices

GaN-based LEDs represent the most commercially mature and extensively researched class of III-nitride optoelectronic devices, serving as the functional cornerstone for flexible optoelectronic systems (Fig. 3.1). Fundamentally, the operation of GaN LEDs relies on the spontaneous emission of photons through the radiative recombination of injected electrons and holes within (In,Ga)N/GaN multiple quantum wells (MQWs). Compared with previous light sources (*e.g.*, fluorescent lamps), LEDs offer distinct operational advantages, including lower driving voltages, superior wall-plug efficiency and the technical feasibility of large-area monolithic^{67,68}. These intrinsic attributes render them ideal candidates for high-resolution flexible displays, conformal wearable lighting and sophisticated bio-integrated photonic interfaces.

To bridge the technological gap between rigid epitaxy and flexible functionality, several transformative strategies have emerged. A paradigm shift in this field is the advent of remote epitaxy and vdW integration (*e.g.*, employing graphene buffer layers). This approach facilitates the seamless, non-destructive exfoliation of single-crystalline GaN membranes, which can subsequently be transferred onto arbitrary flexible substrates without compromising their inherent crystalline perfection⁶⁹. Recent breakthroughs have demonstrated the potential of vertically-stacked full-color micro-LEDs. As illustrated in Fig. 3.2a, this architecture bypasses the resolution bottlenecks inherent in traditional lateral pick-and-place methods by stacking red-green-blue (RGB) functional membranes. For instance, Fig. 3.2b displays AlGaAs-based red LEDs grown on graphene-coated GaAs wafers, alongside optical images of the resulting LED membranes transferred onto thermal release tapes (TRT), highlighting their exceptional mechanical flexibility. Furthermore, Fig. 3.2c presents optical and electroluminescence (EL) micrographs of vertical micro-LED arrays tailored for near-eye display applications, featuring seven distinct pixel sizes with densities ranging from 1,000 to

5,100 pixels per inch (PPI). Such vertically integrated structures achieve unprecedented pixel densities while maintaining superior mechanical compliance⁷⁰. Table 2 presents a performance comparison among LCD, OLED, and micro-LED, highlighting the significant advantages of Micro-LED in current device applications.

Table 2. Quantitative performance comparison of LCD, OLED and Micro-LED

Performance metric	LCD	OLED	Micro-LED
Luminance (cd/m ²)	500–3,000	800–1,500	>100,000
Contrast ratio	1,000,000:1	Infinite	Infinite
Power consumption (relative)	High	Low	Lowest
Response time	1–5 ms	~0.1 ms	~1 ns
Lifespan (hours)	60,000–100,000	30,000–50,000	>100,000
Color gamut (% NTSC)	72–90	100–120	>120
Viewing angle (deg)	~170 (IPS)	~178	~178
Flexibility	Limited	Excellent	Excellent
Pixel density (PPI, max)	~800	~600	>5,000
Operating temperature (°C)	0 to 50	–20 to 70	–100 to 120
Ref.	71	72	1,73,74

Beyond individual device architectures, the research frontier has expanded toward high-throughput mass transfer for large-scale system integration. Advanced fluidic self-assembly (FSA) has pushed the boundaries of integration efficiency, enabling the autonomous assembly of 18 μm -sized GaN chiplets with yields exceeding 99.7% and throughput rates surpassing 12,000 units per minute⁷⁵. This progress is further augmented by the integration of quantum dot (QD) color conversion layers and 2D material-based transparent electrodes, which collectively broaden the color gamut and optimize current spreading in stretchable display matrices⁷⁶.

Despite these sophisticated advances, several critical challenges persist. These include mechanical fatigue under long-term cyclic loading and the acute thermal management issues arising from the low thermal conductivity of polymeric substrates. Future

research trajectories are increasingly focused on high-fidelity heterogeneous integration and active-matrix driving designs, aiming to dissipate the remaining barriers between laboratory prototypes and commercial-grade flexible GaN photonic chips.

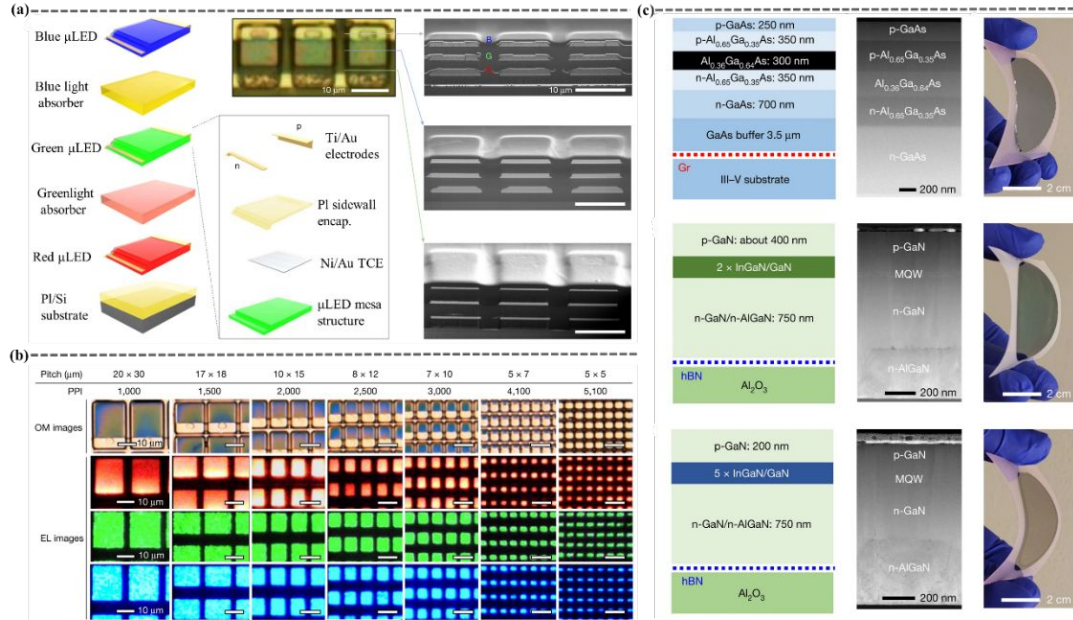


Fig. 3.2 (a) Exploded schematic illustration of a vertical micro-LED pixel and optical microscope image of three vertical micro-LED pixels side by side. (b) Schematic illustrations of the epitaxial structures of an AlGaAs-based red LED, and cross-sectional STEM images of freestanding red, green and blue LED films. (c) Optical and EL microscopy images of vertical micro-LED arrays.⁷⁰ Copyright © 2023, Springer Nature.

3.2 Sensor and Detectors

Flexible GaN-based sensors and photodetectors (PDs) constitute key functional building blocks in III-nitride optoelectronic systems, enabling efficient transduction of optical, chemical and biological signals into electrical outputs. Owing to its intrinsically wide bandgap, GaN exhibits solar-blind ultraviolet (UV) sensitivity, excellent thermal stability and strong radiation tolerance, rendering it particularly attractive for operation in harsh environments and deformable platforms^{77,78}. In recent years, significant

progress has been achieved in flexible GaN photodetectors through structural engineering and substrate transfer strategies. Techniques such as epitaxial layer lift-off, substrate thinning and heterogeneous integration allow GaN devices originally grown on rigid substrates to be transferred onto flexible polymeric or metallic supports while preserving high responsivity and fast temporal response. In particular, (Al,Ga)N/GaN high-electron-mobility transistors (HEMTs) have emerged as promising platforms for high-performance UV photodetection. For instance, Ramit Kumar Mondal *et al.* demonstrated flexible phototransistors based on single-crystalline (Al,Ga)N/GaN heterostructure membranes (Fig. 3.3a). The released membranes can be successfully transferred onto flexible substrates (Fig. 3.3b), yielding flexible photo-HEMT devices with outstanding optoelectronic performance, including a detectivity of 2.7×10^{16} Jones at 360 nm⁶⁶. Notably, these devices maintain stable photo-response under repeated bending and cyclic strain, highlighting their potential for wearable UV monitoring and flexible imaging systems.

Beyond photodetection, flexible GaN platforms have also been extended to strain-sensitive devices. Renfeng Chen *et al.* developed flexible thin-film sensors exploiting strain-induced polarization modulation at the GaN/Ti interface. The stress distribution under bending and the corresponding variations in photocurrent and dark current under tensile strain are illustrated in Fig. 3.3c⁷⁹. This work advances the development of flexible sensors based on wurtzite III–V nitrides, with implications for wearable electronics and optoelectronic sensing applications^{80,81}. Moreover, by integrating functional transduction layers, GaN-based devices can be extended into multifunctional sensing platforms capable of detecting strain, pressure and biochemical signals. Dong Won Yang *et al.* reported a novel strategy for fabricating 3D microcrystal LEDs, exhibiting a wavelength shift of approximately 50 nm under applied stress up to 8 MPa. As shown in Fig. 3.3d⁸², the EL spectra and finite element simulations of strain distribution under external stress (0–7.7 MPa) reveal stress-dependent emission variations originating from the MQWs. Such multimodal sensing capability enables the

realization of flexible electronic skin systems that respond simultaneously to optical and mechanical stimuli, with significant potential in wearable electronics and human–machine interfaces.

In addition to conventional planar architectures, low-dimensional GaN nanostructures, including nanowires, nanorods and nanomembranes, offer distinct advantages in enhancing mechanical flexibility and light–matter interaction. For example, Mingzeng Peng *et al.* fabricated nanopillar arrays composed of (In,Ga)N/GaN MQWs, where the photoluminescence (PL) intensity can be tuned linearly and significantly under small strain (0–0.15%) via the piezo-phototronic effect. These sensor arrays exhibit an ultrahigh pixel density of 6,350 dpi and minimal PL variation. As shown in Fig. 3.3e, the strain-modulated PL imaging (i), PL spectra (ii), and PL intensity evolution (iii) under different compressive stresses demonstrate the effectiveness of this approach. Benefiting from their high surface-to-volume ratio and superior strain accommodation, such nanostructures enhance carrier collection efficiency and improve photoresponse⁸³. Furthermore, heterogeneous integration of GaN with 2D materials such as graphene and TMDs can further optimize carrier transport and enable broadband photodetection, thereby expanding device functionalities.

At the system level, flexible GaN sensors and photodetectors can be integrated with light sources and neuromorphic computing units to form closed-loop optoelectronic systems capable of real-time signal acquisition, preprocessing and decision-making. These systems hold considerable promise for applications in wearable health monitoring, environmental sensing, artificial skin and implantable diagnostic devices. Despite these advances, challenges remain in achieving large-area uniformity, long-term mechanical reliability and low dark current under bending conditions. Future efforts focusing on interface engineering, nanostructure design and advanced heterogeneous integration are expected to further enhance device performance and accelerate the deployment of flexible GaN-based systems in next-generation

optoelectronics.

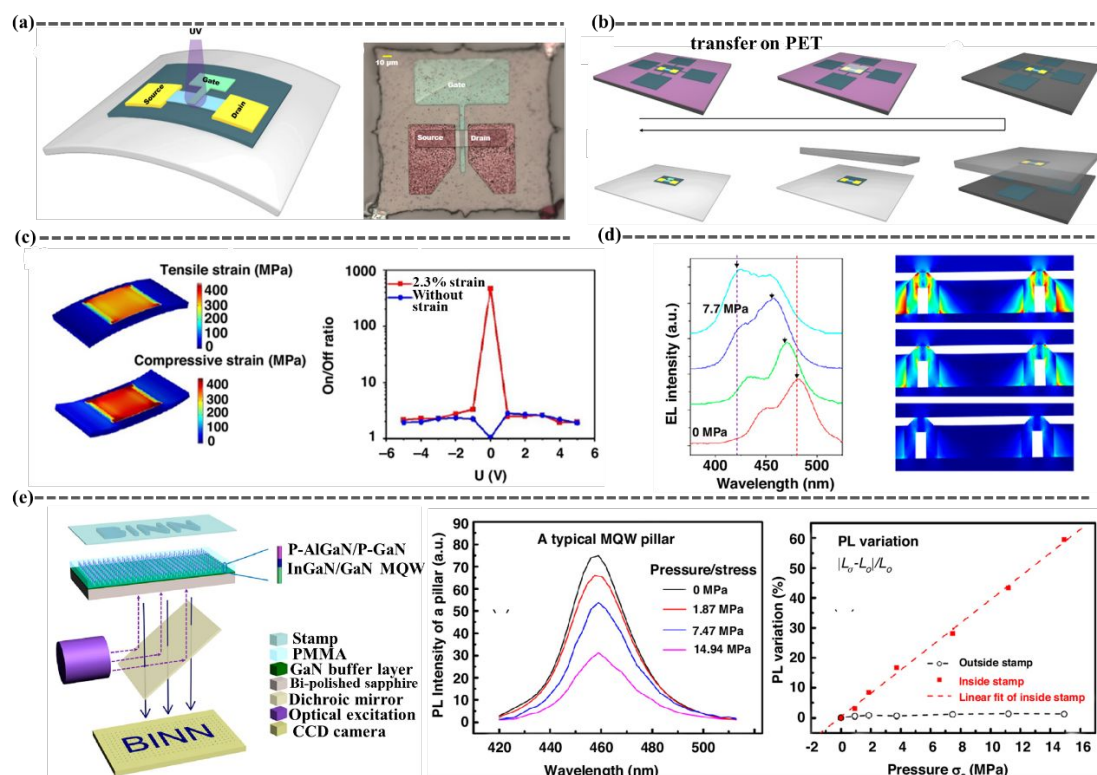


Fig. 3.3 (a) Schematic diagram and top-view microscopic image of (Al,Ga)N/GaN flexible photo-HEMT transferred on PET. (b) Transfer printing process of flexible (Al,Ga)N/GaN photo-HEMT.⁶⁶ Copyright © 2026, American Chemical Society. (c) Stress distribution of the sensor under bending and the ratio of light/dark current under tensile strain and without strain.⁷⁹ Copyright © 2024, IOP Publishing. (d) EL spectra and FEA simulation of the strain distribution under external stress increased from 0 to 7.7 MPa.⁸² Copyright © 2020, American Chemical Society. (e) Schematic diagram of piezo-phototronic effect tuned PL spectra and PL intensity under various compressive stresses.⁸³ Copyright © 2015, American Chemical Society.

3.3 Laser

GaN-based laser diodes (LDs) provide highly coherent, high-intensity and strongly directional optical emission, distinguishing them from LEDs and establishing them as key light sources for high-speed optical communication and on-chip photonic integration. In flexible optoelectronic systems, such high-quality emitters are particularly critical for enabling high-bandwidth signal transmission and dense photonic integration.

From a device physics perspective, GaN lasers typically rely on (In,Ga)N/GaN MQW structures to achieve stimulated emission. Their performance is governed by carrier injection efficiency, optical confinement and defect density. In recent years, substantial progress in epitaxial growth and device design has enabled high-power and high-efficiency GaN lasers. Early pioneering work by Shuji Nakamura and co-workers established the foundation for blue GaN laser diodes, followed by advances enabling high-power continuous-wave (CW) operation, which have become essential for industrial processing and display technologies. More recently, Yang *et al.* demonstrated optically pumped vertical-cavity surface-emitting lasers (VCSELs) operating in the ~ 350 nm spectral range⁸⁴. As illustrated in Fig. 3.4a, the fabrication process involves dual-dielectric distributed Bragg reflectors and an Al-containing cavity, realized on Si (100) substrates through substrate transfer and laser lift-off techniques. The resulting VCSELs exhibit lasing at wavelengths as short as ~ 356 nm, below the GaN band edge. As shown in Fig. 3.4b, the PL spectra under 356 nm excitation, along with the evolution of emission intensity and linewidth as a function of pump power density, confirm lasing behavior. The UV-A VCSEL exhibits a threshold pump power density of ~ 0.8 MW cm⁻², among the lowest reported for UV VCSELs⁸⁴. In addition, Feng Feng *et al.* developed high-power (Al,Ga)N-based deep-UV micro-LED arrays for maskless lithography⁵⁹. Feifan Xu *et al.* reported a scalable strategy for fabricating continuous-wave (CW) electrically pumped whispering-gallery mode (WGM) blue micro-lasers

based on III-nitride semiconductors (Fig. 3.4c)²⁷. These devices, with diameters spanning 10 to 160 μm , feature low threshold current density and high slope efficiency. Such excellent performance is realized via effective vertical optical confinement from the waveguide structure and negligible sidewall scattering owing to the atomically smooth sidewall surfaces.

From a structural perspective, semipolar and nonpolar GaN laser diodes have attracted increasing attention. Compared with conventional c-plane GaN, these orientations effectively suppress the QCSE, thereby enhancing radiative recombination efficiency and reducing threshold current density. Studies led by Nakamura and others have demonstrated that semipolar GaN lasers offer clear advantages in high-power output and high-speed modulation, making them promising candidates for visible light communication²¹. For example, Changmin Lee *et al.* reported a semipolar GaN laser diode operating at 410 nm, achieving a modulation bandwidth of 6.8 GHz along with favorable dynamic characteristics⁸⁵. To address the demands of high-precision optical communication and sensing, distributed feedback (DFB) GaN lasers have also been developed. By introducing grating structures to enforce single-mode operation⁸⁵, these devices exhibit narrow linewidths and high spectral purity. Such properties make DFB GaN lasers particularly attractive for on-chip photonic systems and high-resolution spectroscopic applications. For laser-based display and lighting applications, blue laser diodes are invariably fabricated on free-standing GaN substrates. Heteroepitaxy of (In,Ga)N/GaN multiple quantum wells on cost-effective and large-diameter Si substrate offers a viable route to significantly reduce the production cost of blue laser diodes. Yi Sun and co-workers inserted a step-graded AlN/(Al,Ga)N multilayer buffer between the GaN layer and the Si substrate to manage lattice mismatch and thermal stress (Fig. 3.4d). During the growth of the GaN quantum barriers, hydrogen is introduced, and the growth temperature of the p-type (Al,Ga)N/GaN superlattice optical confinement layer is lowered. These measures eliminate In-rich clusters and effectively suppress thermal degradation of the (In,Ga)N/GaN blue multiple quantum wells. As a result, they

successfully demonstrated room-temperature continuous-wave electrically pumped (In,Ga)N/GaN blue laser diodes directly grown on Si substrates⁶⁰, with an emission wavelength of 450 nm and a threshold current density of 7.8 kA/cm².

In terms of mechanical adaptability, conventional GaN lasers are limited by their reliance on rigid substrates. However, recent advances in epitaxial lift-off and heterogeneous integration have enabled viable pathways toward flexible GaN lasers. By transferring GaN active layers onto flexible substrates such as polyimide films or metal foils, mechanical deformability can be achieved without compromising optical performance. Notably, GaN microscale light sources fabricated via transfer techniques have been shown to maintain stable emission characteristics under repeated bending, providing a foundation for flexible laser technologies⁶⁴. At the materials level, low-dimensional GaN nanostructures offer an alternative route to flexible lasing. Justin C. Johnson *et al.* first demonstrated lasing from a single GaN nanowire, which functions simultaneously as both gain medium and optical cavity. Subsequently, Qiming Li *et al.* realized single-mode GaN nanowire lasers with narrow linewidths and excellent mode selectivity (Fig. 3.4e)⁶⁴. Owing to their high strain tolerance, such nano-lasers can sustain stable operation under bending or stretching, exhibiting an intrinsic flexibility. Further integration of GaN nano-lasers with micro- and nano-photonic structures enables reduced lasing thresholds and device miniaturization, including whispering-gallery-mode (WGM) resonators, photonic crystals and plasmonic architectures. For instance, GaN lasers based on WGM microcavities can achieve stable lasing at low pump power while maintaining high-quality factors (Q factors), providing efficient light sources for flexible on-chip photonic systems. Importantly, these structures can preserve stable optical modes under mechanical deformation, which is essential for flexible photonic circuitry.

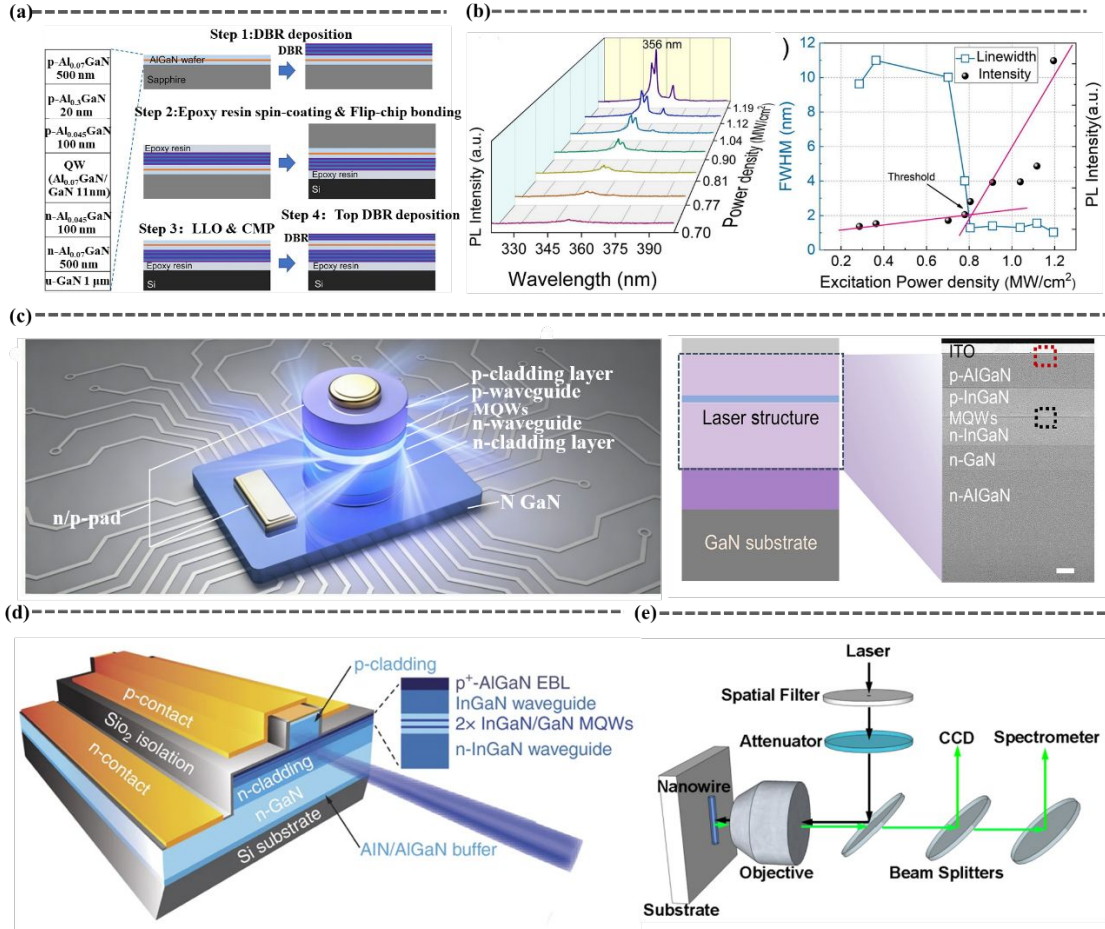


Fig. 3.4 (a) Epi-structure and device fabrication processes of the UVA VCSEL. (b) Excitation energy dependent PL spectra of the VCSEL lasing at 356 nm and Intensity and linewidth of the device as a function of excitation power density.⁸⁴ Copyright © 2026, Elsevier. (c) Schematic images of a GaN laser epitaxial structure and a GaN-based micro-disk laser.²⁷ Copyright © 2026, The American Association for the Advancement of Science. (d) Schematic structure of a blue laser directly grown onto a Si substrate.⁶⁰ Copyright © 2018, Springer Nature. (e) Schematic of the GaN nanowire optical pumping and measurement setup.⁶⁴ Copyright © 2024, Optica Publishing Group.

In addition, the GaN platform has recently emerged as a promising candidate for quantum photonics. By introducing defect states or engineered quantum structures, GaN can support single-photon emission and quantum light sources, opening new possibilities for flexible quantum devices. These developments further expand the application landscape of GaN lasers in information processing and secure

communication. From an application perspective, flexible GaN lasers show considerable potential in wearable optical communication (*e.g.*, LiFi), flexible optical interconnects, bio-photonics and neural interfaces. Their high modulation bandwidth and environmental robustness enable reliable data transmission under dynamic mechanical deformation. Furthermore, integration with sensors and neuromorphic components may enable fully integrated sensing–communication–computing flexible systems.

Despite these advances, flexible GaN lasers remain at an early stage of development, with key challenges in thermal management, device reliability and large-scale integration. Future progress will likely depend on improved epitaxial quality, the development of advanced flexible substrates and the incorporation of innovative photonic designs, ultimately paving the way toward high-performance, scalable flexible photonic chips.

3.4 Synaptic Devices

Flexible GaN-based neuromorphic devices have recently emerged as an important research direction within III-nitride optoelectronics, demonstrating significant potential for brain-inspired computing and artificial perception systems. Benefiting from the intrinsically wide bandgap, strong polarization effects and excellent environmental stability of GaN, these devices are capable of emulating key synaptic functions, including short-term plasticity (STP), long-term potentiation (LTP) and learning–forgetting processes. Compared with conventional oxide-based memristive systems, GaN-based devices offer superior stability and are inherently compatible with optical signal modulation, making them particularly attractive for flexible optoelectronic neuromorphic platforms. Table 3 presents the findings of different researchers on neural synapses, along with their respective characteristics.

Table 3. Key performance comparison of GaN-based artificial synaptic devices.

Device structure	PPF index (%)	LTP, LTM, STDP	Key performance metrics	Flexible	Ref
(Al,Ga)N/GaN + SiN _x	150%	LTM>10years	ON/OFF>10 ³ ,8 levels	Rigid	86
(Al,Ga)N/GaN transistor	138%	LTP, LTM	EPSC~1.2μA, dark current 0.1nA	Rigid	87
(Al,Ga)N NW/graphene	–	LTP/LTD~2.5	Power 2.6μJ/spike	Flexible	88
Three-terminal GaN NW	–	LTP,LTM,STDP	Accuracy>95%, Gate enhancement>1000%	Flexible	89
p-(Al,Ga)N/n-GaN NW	–	LTM>10 ³ s	τ ₁ ~0.7s, τ ₂ ~6.8s	Potential	90
Si-doped GaN MSM	120%	LTM>10 ⁴ s	Transition at 100 pulses	Rigid	91
Graphene/(Al,Ga)N NW dual-mode	160%	LTP, LTM	Energy 2.5×10 ⁻¹⁴ J, rejection 1.29×10 ⁴	Flexible	92
(Al,Ga)N NW/graphene imaging	145%	LTP	Dynamic range>10 ³	Flexible	93

At the device level, synaptic behavior in GaN systems primarily arises from carrier trapping and detrapping processes, persistent photoconductivity (PPC) and interface state modulation. Through precise heterostructure engineering, stable and tunable multilevel conductance states have been achieved. For example, Cuihong Kai *et al.* developed an optoelectronic synaptic device with long-term memory (LTM) functionality based on a GaN/(Al,Ga)N/AlN/GaN heterostructure incorporating a SiN_x charge-trapping layer (Fig. 3.5a)⁶¹. The device successfully reproduces key synaptic characteristics, including excitatory postsynaptic current (EPSC), paired-pulse facilitation (PPF) and the transition from short-term memory (STM) to LTM. Notably, the retention time of LTM exceeds 10 years, indicating excellent charge storage reliability. In addition, logic functions can be implemented through the synergistic operation of optical and electrical gating⁶¹. Similarly, Xiaoqi Li *et al.* reported an optically tunable synaptic transistor based on an (Al,Ga)N/GaN heterostructure for neuromorphic vision processing. As shown in Fig. 3.5b, the device enables optical modulation of synaptic behavior while maintaining low dark current and high

photoresponsivity, and exhibits synaptic plasticity features such as EPSC, PPF and the transition from STM to LTM. These results confirm the feasibility of (Al,Ga)N/GaN synaptic devices for neuromorphic visual processing and highlight their potential as building blocks for brain-inspired computing hardware⁹⁴.

From a structural perspective, low-dimensional GaN nanostructures, particularly nanowire systems, play a critical role in flexible neuromorphic devices. For instance, we developed a dual-mode monolithic device based on an (Al,Ga)N nanowire/graphene heterojunction, which could operate as a photodetector under negative bias and as a neuromorphic sensor under positive bias (Fig. 3.5c-3.5e). The device architecture (Fig. 3.5f), along with its demonstrated image acquisition and processing pathway (Fig. 3.5g and 3.5h), illustrates an integrated framework in which artificial synaptic elements perform initial visual preprocessing prior to recognition by an artificial neural network¹¹. In the previous study, we designed a graphene/(Al,Ga)N nanowire heterostructure that enables the monolithic integration of a self-powered 360° photodetector and an artificial synapse within a dual-mode transparent device. As shown in Fig. 3.5c, the device configuration aligns closely with biological synaptic structures, while its UV/visible rejection ratio at -2 V bias demonstrates effective spectral selectivity. Furthermore, Fig. 3.5d presents the EPSC characteristics and low power consumption under varying stimulation frequencies (1, 5 and 10 Hz) at -0.1 V bias, highlighting its potential for next-generation low-power neuromorphic computing systems¹². Owing to their high surface-to-volume ratio and excellent strain tolerance, GaN nanowires enhance electric field modulation while maintaining stable performance under mechanical deformation, underscoring their importance for high-performance flexible synaptic devices.

From an architectural standpoint, the introduction of three-terminal GaN synaptic transistors significantly improves the precision and programmability of synaptic modulation. Lifeng Bian *et al.* reported a three-terminal GaN nanowire synaptic device

in which synaptic conductance can be continuously tuned via gate control⁹⁵. As illustrated in Fig. 3.5e, the device is fabricated using an electrophoretic assembly process. It is capable of emulating PPF, spike-timing-dependent plasticity (STDP) and learning–forgetting–relearning behaviors, and achieves recognition accuracy exceeding 95% in neural network simulations. Compared with conventional two-terminal devices, this approach effectively mitigates the stochasticity of synaptic weight modulation, representing a key step toward high-precision neuromorphic computing.

In addition to nanowire-based systems, GaN thin films also provide a viable platform for neuromorphic devices⁹⁵. For example, a simple two-terminal optically stimulated synaptic device has been demonstrated using GaN thin films grown by metal–organic chemical vapor deposition (MOCVD). In this approach, Si-doped, Mg-doped and undoped GaN films are deposited on sapphire substrates to fabricate metal–semiconductor–metal (MSM) artificial synapses with an Ag/GaN/Ag configuration. Among these, Si-doped GaN devices exhibit a range of synaptic-like behaviors, including STM-to-LTM transition, PPF and learning processes. As shown in Fig. 3.4i, the device can emulate human learning and experience behaviors under continuous optical pulse stimulation, demonstrating its feasibility for neuromorphic computation. This work provides a simple and effective strategy for developing optically stimulated synaptic devices with high performance^{96,97}.

At the system level, flexible GaN synaptic devices can be further integrated with photodetectors and light-emitting components to form closed-loop neuromorphic vision systems. In such architectures, optical signal sensing, processing and storage are co-located within a single platform, enabling a “sensing-in-memory” or “perception-in-computing” paradigm. This integration can significantly reduce data transfer latency and energy consumption, offering substantial advantages for applications in artificial skin, intelligent robotics, wearable electronics and brain–machine interfaces.

Despite these advances, flexible GaN neuromorphic devices still face several challenges, including the stability of multilevel conductance states, LTM retention under mechanical strain and device-to-device uniformity at large scale. Future efforts focusing on defect engineering, interface control and high-density integration strategies are expected to further advance GaN-based neuromorphic devices toward high-performance, low-power and scalable flexible intelligent systems.

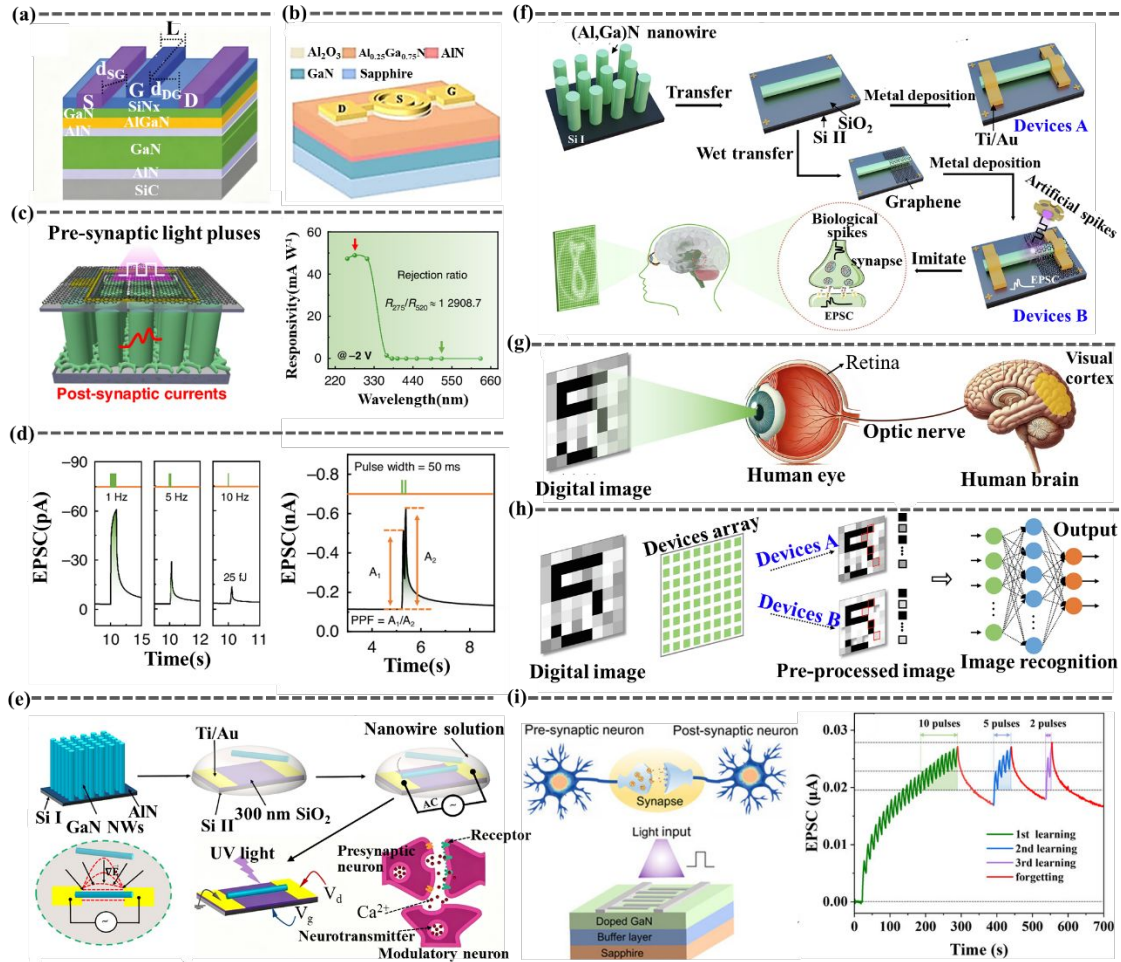


Fig. 3.5 (a) Schematic and photoelectronic transport of the synaptic device.⁶¹ Copyright © 2023, Wiley. (b) Schematic of an (Al,Ga)N/GaN synaptic device.⁹⁴ Copyright © 2025, AIP Publishing. (c) Schematic diagram showing the components of a dual-mode transparent device that align with the biological synaptic architecture, and the UV/visible light rejection ratio of the device under -2 V bias voltage. (d) EPSC with a wavelength of 310 nm. and power consumption of the device under 9.2 $\mu\text{W cm}^{-2}$ at -0.1 V bias.⁶² Copyright © 2025, Springer Nature. (e) Schematic procedure and

experimental results of preparing a synaptic nano-device by dielectrophoretic method.⁹⁵ Copyright © 2026, Wiley-VCH GmbH. (f) Schematic diagrams of device preparation processes and digital recognition. (g, h) Two schematic diagrams of initial visual perception and an image pre-processed system.¹¹ Copyright © 2025, Springer Nature. (i) Schematic illustration of the synaptic device, the biological synapse and the use of continuous light pulses to replicate the learning and experience behavior of the human brain.⁵³ Copyright © 2025, Wiley-VCH GmbH.

4. Methods for Flexibility

Flexible integration of GaN-based devices relies critically on advanced structural and processing strategies that decouple the intrinsically rigid III-nitride materials from their conventional substrates. Unlike organic or low-dimensional materials, GaN possesses high Young's modulus and is typically grown on rigid substrates such as sapphire, Si or SiC, which inherently limits its mechanical deformability. Therefore, achieving flexibility in GaN systems is not a material property issue, but rather a structural and engineering challenge. Over the past decade, several key approaches have been developed to enable mechanical flexibility in GaN-based devices, including epitaxial lift-off, mass transfer techniques and structural engineering of device architectures. These methods allow high-performance GaN optoelectronic components, such as LEDs, photodetectors, lasers and synaptic devices, to be integrated onto flexible and stretchable substrates without significantly degrading their electrical or optical properties. In this chapter, we systematically review the major strategies for realizing flexibility in GaN-based systems, with a focus on their mechanisms, advantages, limitations and applicability to large-scale integration.

4.1 Lift-off Methods

The lift-off technologies that enable the separation of epitaxial layers from their native substrates^{72,98}, followed by transfer onto flexible supports, have become a central strategy for constructing flexible GaN devices. MOCVD remains the dominant method for GaN epitaxy, owing to its advantages in compositional control, thickness uniformity and scalability. In recent years, efforts have extended beyond improving epitaxial quality to engineering the growth stage itself to facilitate subsequent release. For example, Tobiloba Grace Fabunmi *et al.* employed graphene as an interfacial buffer layer to achieve controlled growth of single-crystalline GaN micro-disk arrays via MOCVD, which were directly implemented in flexible LED devices (Fig. 4.1a)⁹⁹. This

“weakly coupled interface” strategy eliminates the need for conventional sapphire removal, offering an alternative pathway to flexible devices without complex lift-off processes. Similarly, Seungmin Lee *et al.* demonstrated core-shell GaN micro-LED arrays grown on ultrathin sapphire nanomembranes, achieving both reduced dislocation density and mechanical releasability (Fig. 4.1b)¹⁰⁰, exemplifying the emerging concept of epitaxy-enabled lift-off.⁹⁹

To address the inherent brittleness of thick GaN films, alternative structural approaches based on inorganic nanowires and micro-rods (MRs) have also been explored. Owing to their reduced lateral dimensions and enhanced strain relaxation along sidewalls, such one-dimensional structures can significantly suppress defect formation in the device region. In addition, remote epitaxy has been introduced as a versatile approach to obtain single-crystalline overlayers, in which crystallographic registry is guided through atomically thin interlayers (*e.g.*, graphene). This method enables the growth of high-quality nanowires on lattice-matched substrates, followed by their non-destructive release without damaging the underlying wafer. As illustrated in Fig. 4.1c, this strategy enables deformable LED fabrication through remote heteroepitaxy of micro-rod arrays and subsequent transfer onto conductive metal substrates, while Fig. 4.1d highlights the resulting mechanical flexibility¹⁰¹.

Despite these advances, most high-performance GaN devices still rely on heteroepitaxial growth on rigid substrates, making post-growth lift-off processes indispensable. Among the available techniques, laser lift-off (LLO) is the most widely adopted. In this approach, UV laser irradiation, typically at 248 nm or 266 nm, is directed at the GaN/sapphire interface, inducing photothermal or photochemical decomposition that generates metallic Ga and enables rapid separation of the epitaxial layer. LLO has been extensively applied to the transfer of micro-LEDs, GaN photodetectors and thin-film lasers, while largely preserving device performance. To further improve yield and alignment accuracy, tape-assisted laser transfer (TALT) has

been developed, in which a mechanical support layer enhances the uniformity and stability of large-area transfer¹⁰². The physical mechanism of laser lift-off is based on photothermal decomposition. When a high-energy UV laser pulse (typically 248 nm or 266 nm) is directed through the transparent sapphire substrate and absorbed at the GaN/sapphire interface, the optical energy rapidly converts into heat. The local temperature rises above 1000 °C within nanoseconds, causing the interfacial GaN to dissociate into metallic gallium and nitrogen gas ($2\text{GaN} \rightarrow 2\text{Ga} + \text{N}_2 \uparrow$). The generated liquid gallium layer acts as a lubricant, drastically reducing the adhesion energy and enabling the epitaxial layer to be mechanically separated from the substrate with minimal damage. For electrochemical lift-off, the mechanism involves selective electrochemical etching of a sacrificial layer (*e.g.*, a thin GaN or (Al,Ga)N layer) in an electrolyte solution under an applied bias. The etching proceeds along dislocation pipes or intentionally introduced porous layers, weakening the interfacial bonding and allowing intact release¹⁰³.

Beyond LLO, low-damage lift-off techniques have attracted increasing attention. Electrochemical lift-off, in particular, has emerged as a promising alternative. Wenfeng Li *et al.* demonstrated that electrochemical etching in nitric acid electrolyte can effectively weaken the interfacial bonding between GaN and its substrate, enabling the intact release of micro-LED arrays. In parallel, flexible HEMTs have also been realized using this approach, which are critical for radio-frequency and wireless communication applications. For example, Xin Chen *et al.* successfully employed electrochemical lift-off to transfer large-area ($>2 \text{ cm}^2$) (Al,Ga)N/AlN/GaN heterostructures onto flexible polyethylene terephthalate substrates (Fig. 4.1e). Compared with LLO, this method offers reduced stress and minimized damage, and has been extended to a variety of GaN-based devices, demonstrating broad applicability⁸.

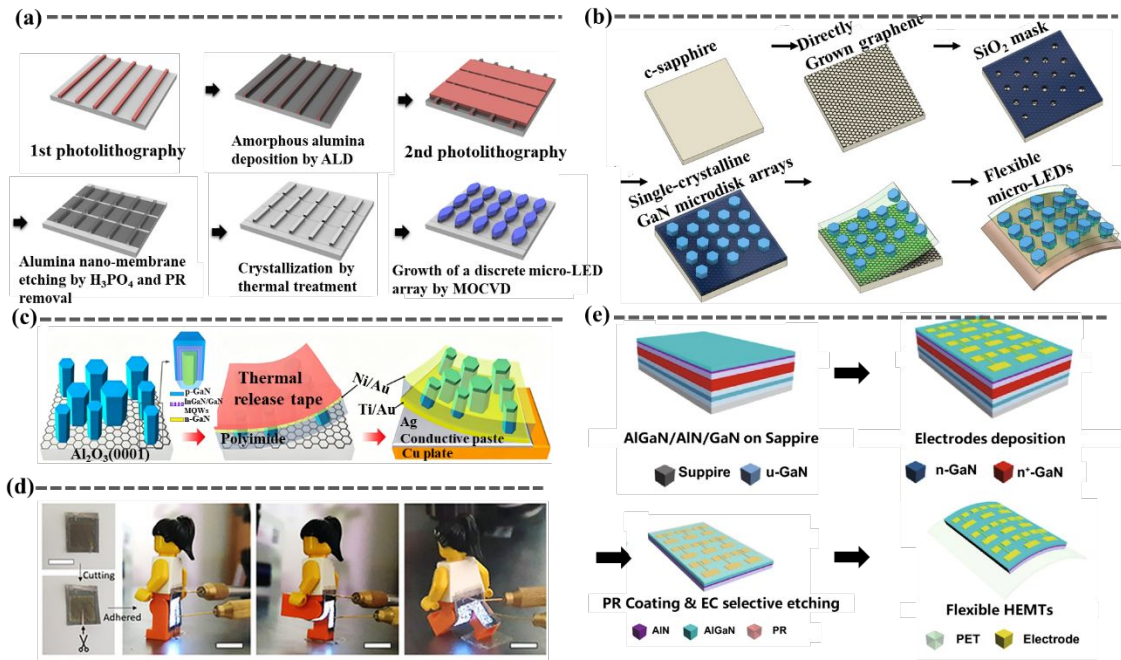


Fig. 4.1 (a) Schematic diagram for the fabrication of micro-LED array.¹⁰⁰ Copyright © 2020, Springer Nature. (b) Schematic illustration of the fabrication process for flexible GaN micro-LEDs.⁹⁹ Copyright 2023, IOP Science. (c) Schematic of the key procedures for fabricating the deformable LED. (d) Photographs of the device tailored to be fitted to two back legs of a minifigure.¹⁰¹ Copyright © 2020, The American Association for the Advancement of Science. (e) The HEMT debonding and transition processes.⁸ Copyright © 2021, Springer Nature.

Another emerging approach is electrocapillary peeling (ECP), in which an applied electric field drives electrolyte infiltration at the interface, inducing interfacial failure and enabling non-contact film release. By avoiding thermal effects, ECP minimizes damage and is particularly suitable for structurally sensitive systems such as nanowire arrays and quantum photonic devices. Although still in its early stages, this method shows strong potential for achieving high-yield, low-damage transfer¹⁰⁴.

Interface engineering provides an additional route for improving lift-off quality. For instance, functionalization of substrate or interlayer surfaces with thiol ($-SH$) groups can precisely modulate interfacial adhesion, transforming strong bonding into

controllable weak interactions. This approach not only enables deterministic release but also improves transfer accuracy for microscale devices, such as micro-LED pixel arrays. Beyond the lift-off process itself, structural design plays a crucial role in enabling flexibility. For example, wafer-scale sapphire nanomembranes can serve both as high-quality epitaxial templates and as releasable platforms, thereby eliminating the need for conventional dicing and improving transfer efficiency. Similarly, the introduction of suspended structures or sacrificial layers on Si(111) substrates enables selective release, providing additional design freedom for flexible GaN devices^{105,106}.

Overall, lift-off technologies for GaN have evolved from simple substrate removal methods into integrated strategies that combine epitaxial design, interface engineering and advanced processing techniques. Importantly, these approaches are not limited to micro-LEDs but are broadly applicable to flexible photodetectors, laser devices and neuromorphic systems. Future research will likely focus on minimizing process-induced damage, improving large-area uniformity and enabling high-throughput manufacturing, thereby accelerating the practical deployment of flexible GaN-based electronic and photonic systems.

4.2 Mass Transfer

Flexible micro-LED displays fabricated through chip transfer necessitate mass transfer technology, which is distinct from monolithically integrated devices. This process aims to precisely and efficiently relocate millions to tens of millions of micro-LED chips from their growth substrates to target driving backplanes¹⁰⁷. Current research focuses on developing diverse mass transfer methodologies, which face the critical challenge of maintaining $\pm 0.5\ \mu\text{m}$ alignment accuracy while handling such vast quantities of micro-devices. Predominant techniques for flexible micro-LED systems include laser-induced forward transfer (LIFT), elastomer stamp-based roll-to-roll (R2R) processes utilizing polydimethylsiloxane (PDMS), and fluidic self-assembly approaches^{108,109}.

Table 4 presents the specific data for different transfer methods, along with their respective characteristics.

Table 4. Comparison of mainstream mass transfer technologies^{110–115}.

Technology	Principle	Alignment accuracy	Transfer yield	Throughput	Chip size	Key advantage
LIFT	Laser pulse propulsion	$\pm 1.5 \mu\text{m}$	99.9%	~ 700 chips/s	$> 3 \mu\text{m}$	Non-contact, high precision
Roll-to-roll	Adhesion control	$\pm 3\text{--}5 \mu\text{m}$	99.9%	> 1 million chips/h	$> 10 \mu\text{m}$	Scalable, selective transfer
FSA	Capillary shape matching	Submicron	99.88%	$> 12,000$ units/min	$> 10 \mu\text{m}$	Parallel assembly, low cost per chip

4.2.1 Laser Transfer

Micro-LEDs have emerged as one of the most promising GaN-based display technologies, owing to their small pixel size (typically $1\text{--}100 \mu\text{m}$), self-emissive nature, high efficiency and long operational lifetime. These attributes position micro-LEDs as strong contenders to replace conventional liquid crystal displays (LCDs) and organic LEDs (OLEDs). However, achieving flexible integration critically depends on scalable and high-precision transfer technologies, among which laser-based approaches are particularly well suited^{116–118}.

LIFT has attracted considerable attention as a non-contact, high-precision and high-throughput technique for the massive transfer of micro-LEDs¹¹⁵. In most implementations, LLO serves as a prerequisite step, enabling the separation of micro-LED chips from their native growth substrates, typically sapphire. In this process, UV laser irradiation (*e.g.*, 248 or 266 nm) is applied to the GaN/sapphire interface, inducing interfacial decomposition and generating metallic Ga, thereby allowing the epitaxial layer to be cleanly released (Fig. 4.2a). This step is critical for preserving chip integrity

prior to transfer. Following lift-off, LIFT enables the precise placement of micro-LED chips onto a target substrate, often via a transparent carrier coated with a transfer layer. For flexible micro-LED fabrication, this technique offers both high spatial resolution and non-contact operation, enabling patterning with micro- or even nanoscale precision. Such accuracy is essential for micro-LED chips^{119,120}, while the non-contact nature avoids the mechanical damage often associated with conventional pick-and-place methods. The combined LLO–LIFT workflow (Fig. 4.2b) thus provides an effective route for achieving high-yield, low-damage transfer. Laser-induced forward transfer (LIFT) operates on the principle of confined vaporization and momentum transfer. The pulsed laser passes through a transparent carrier substrate and is absorbed by a thin dynamic release layer (DRL) or directly by the wafer itself. Rapid heating causes the DRL to undergo either thermal expansion, melting or ablation, generating a high-pressure vapor bubble or shock wave. The expanding vapor propels the chip toward the receiving substrate at high velocity (typically meters per second). The transfer quality depends on the laser fluence, pulse duration and the absorption coefficient of the DRL¹²¹. An optimal fluence range ensures complete release without fragmenting the chip or causing excessive heating. The recently reported in-situ nanoparticle-assisted resonance enhancement improves transfer precision by locally amplifying the optical field at the interface, reducing the threshold fluence and enabling finer pitch transfer¹²².

To meet the stringent requirements of large-scale micro-LED display manufacturing, transfer yield and throughput remain critical challenges¹²². Ultrafast laser systems, owing to their reduced thermal diffusion, have been widely regarded as promising for micro-LED transfer. However, their extremely high peak power and the still not fully understood transfer mechanisms can lead to variability in transfer quality and efficiency¹²³. To address this, Weigao Sun *et al.* introduced an in-situ nanoparticle-assisted resonance enhancement mechanism under picosecond UV laser irradiation, enabling high-precision batch transfer of micro-LEDs with a fine pitch of 20 μm (Fig. 4.2c). This approach achieves transfer yields approaching 99.9%, a transfer rate of ~

700 devices per second and positional errors below $\pm 1.2 \text{ }\mu\text{m}$ ¹²². Moreover, by optimizing laser parameters including energy density, pulse duration, pulse repetition rate and transfer layer materials, transfer yields can reach 99% and even approach 99.9%. For example, Yujie Xie *et al.* improved chip utilization by employing ablative release layers¹²⁴, while Seungman Kim *et al.* achieved transfer rates of up to 700 chips per second using ultrafast pulsed lasers combined with dynamic release layer technologies (Fig. 4.2d)¹²⁵.

From an industrial perspective, laser-based transfer technologies have already demonstrated significant scalability. For instance, Coherent has developed a 248 nm laser-based system capable of transferring GaN micro-LEDs using a mask projection approach¹²⁶. By shaping the UV laser beam into a uniform “top-hat” intensity profile through a photomask and projection optics, the system ensures homogeneous energy delivery across large, enabling the simultaneous transfer of up to 1,000 dies per pulse with high precision ($\pm 1.5 \text{ }\mu\text{m}$) and throughput. Similarly, a massively parallel laser-enabled transfer (MPLET) technology has been introduced based on LIFT principles¹²⁷. As illustrated in Fig. 4.2e, a diffractive optical element splits a single laser beam into multiple sub-beams, each corresponding to an individual micro-LED¹¹⁴. This parallelization significantly enhances throughput, enabling transfer rates of up to 10^8 units per hour for large-area panels and over 5×10^8 units per hour for smaller displays, with placement accuracy within $\pm 1.8 \text{ }\mu\text{m}$.

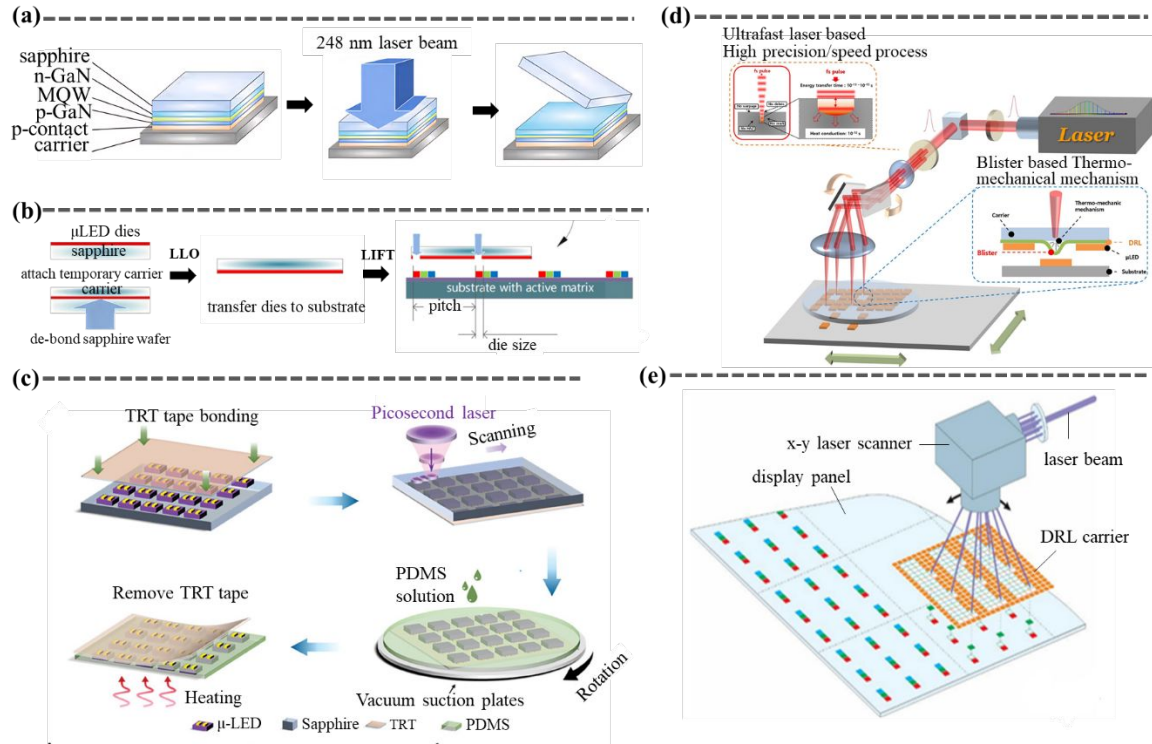


Fig. 4.2 (a) The laser stripping technology developed by Coherent. (b) The micro-LED process employs laser transfer for mass transfer. (c) Schematic illustration of the fabrication process of flexible micro-LEDs.¹²² Copyright © 2024, Wiley. (d) Schematic diagram of a high-precision, high-speed micro-device transfer Process¹²⁵. (e) MPLET schematic diagram.¹¹⁴ Copyright © 2018, The Society for Information Display.

Beyond conventional LIFT, hybrid approaches such as thin-film-assisted laser transfer and bonding (TFA-LTAB) have been proposed. This strategy combines the advantages of laser-induced transfer and bonding processes, using a decomposable thin-film interlayer to facilitate chip release and transfer. Under laser irradiation, the thin film decomposes, enabling controlled detachment and placement of micro-LED chips onto the target substrate. Compared with conventional LIFT, this approach allows for arbitrary pitch transfer, minimizes mechanical contact, and can even support post-transfer repair of defective pixels, potentially achieving near-100% effective yield¹²⁸.

Despite these advances, several challenges remain. One key issue is chip rotation during transfer: after release from the donor substrate, microscale chips may rotate due to

asymmetric geometries or non-uniform mass distribution, leading to reduced placement accuracy and yield. Suppressing such rotation will require further optimization of chip design and laser processing conditions. In addition, residual stress induced during the laser lift-off process can degrade device performance and long-term reliability¹²⁹. Although optimization strategies such as response surface methodology (RSM) have been employed to mitigate stress, more gentle lift-off approaches or post-processing treatments are still needed. Finally, the high cost and complexity of advanced laser systems, particularly femtosecond lasers and precision optical setups, pose challenges for large-scale commercialization. Future efforts should therefore focus on developing cost-effective, scalable and robust laser transfer platforms to fully realize the potential of flexible micro-LED technologies¹³⁰.

4.2.2 Roll-to-Roll Processes

Beyond laser-based approaches, stamp transfer technology represents a mainstream solution for micro-LED mass transfer. This technique typically employs elastomeric stamps (*e.g.*, PDMS) to selectively pick up microscale LED chips and precisely place them onto target substrates. Stamp transfer offers distinct advantages including high transfer accuracy, rapid processing speeds and selective transfer capabilities^{131–133}. PDMS has emerged as the predominant stamp material due to its exceptional elasticity and tunable surface adhesion. By optimizing adhesion forces between the stamp and chips, efficient pick-and-release operations can be achieved (Fig. 4.3a)¹¹⁷. For instance, Hao Lu *et al.* optimized the mass transfer process using a support vector machine (SVM) model to analyze PDMS adhesion stamps, extracting separation velocity and stamp-donor substrate interaction forces as signal features to classify pick-and-place success¹³⁴. Furthermore, PDMS stamp performance can be enhanced through surface micro-structure engineering or carbon doping to improve transfer efficiency and reliability. Modern stamp transfer extends beyond conventional planar pick-and-place methods, which suffer from limited throughput and high costs, to incorporate advanced

techniques such as laser-assisted transfer, thin-film-assisted transfer and thiol-based surface functionalization. These approaches enable precise adhesion control for diverse substrate requirements¹³⁷. The integration of roll-to-roll (R2R) processing with stamp transfer, often involving cylindrical PDMS stamps or roller-based transfer mechanisms, facilitates continuous micro-LED pick-and-place operations that significantly boost production efficiency (Fig. 4.3b and 4.3c)^{135,136,13}. A representative implementation by Ahn *et al.* demonstrates this methodology (Fig. 4.3c)¹³⁷. Their automated R2R system achieves three-stage sequential alignment with real-time feedback control, fabricating flexible micro-LED displays with micro-level positioning accuracy. This advancement highlights the synergistic effect of continuous-motion engineering and elastomer material design, achieving transfer yields exceeding 99.9% at throughputs surpassing 1 million chips per hour. Subsequently, Luhing Hu *et al.* employed this approach to transfer micro-LED arrays from mother substrates to target backplanes (Fig. 4.2b), with the fabricated flexible micro-LED displays applied in gigabit-per-second multichannel visible light communication systems¹³.

The stamp transfer technique relies on the viscoelastic fracture mechanics of elastomeric materials such as polydimethylsiloxane (PDMS). The adhesion between the stamp and a chip is governed by the Johnson-Kendall-Roberts (JKR) contact mechanics model, where the pull-off force is proportional to the work of adhesion and the contact area¹³⁸. Crucially, PDMS exhibits rate-dependent adhesion: at high peeling speeds, the viscoelastic losses increase the effective adhesion energy, allowing the stamp to “pick up” the chip from the donor substrate. At low peeling speeds or during a controlled slow retraction, the adhesion decreases, enabling “printing” onto the target substrate¹³⁹. By modulating the separation velocity and preload force, selective transfer can be achieved without the need for an intermediate adhesive layer.

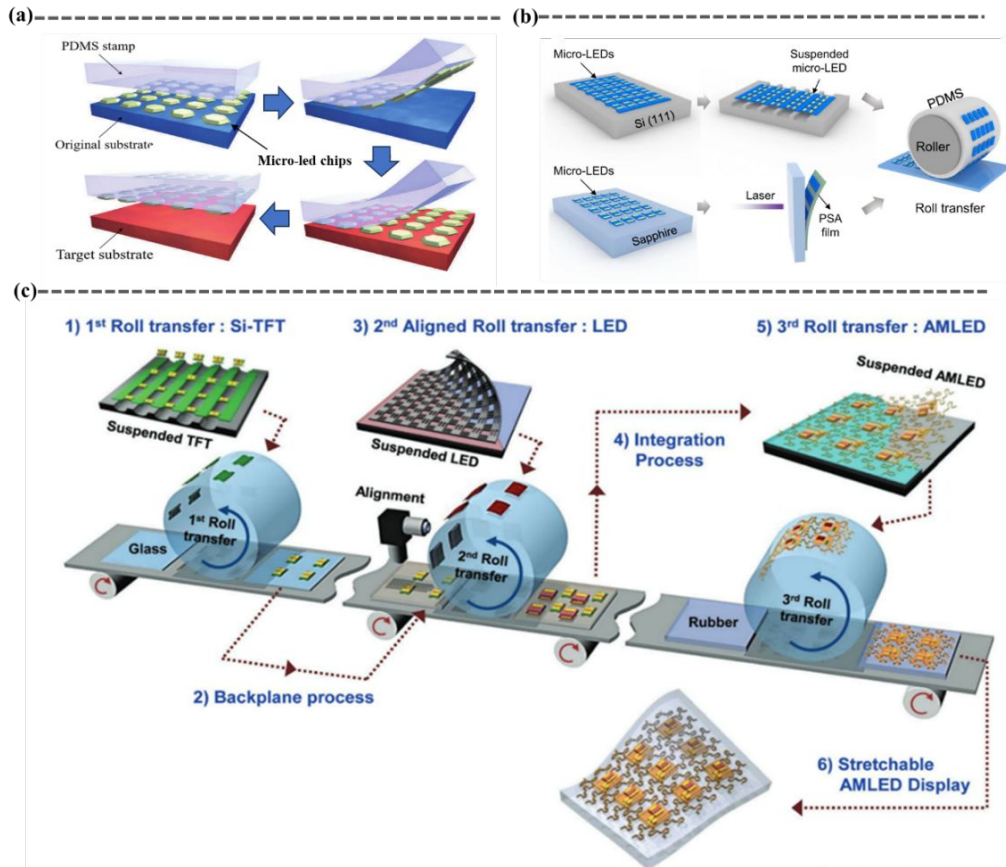


Fig. 4.3 (a) Schematic illustration of transfer printing with a viscoelastic transfer head.¹¹⁷ Copyright © 2022, Springer Nature. (b) Schematic of transferring a micro-LED array from original substrate to target substrate using roll transfer.¹³ Copyright © 2022, Springer Nature. (c) Schematic of steps for assembling the stretchable LED display by the triple roll-transfer technique.¹³⁷ Copyright © 2017, Wiley.

The integration of micro-LED technology with R2R-compatible stamp transfer further enables novel possibilities for flexible and full-color displays. R2R processes facilitate the fabrication of micro-LED arrays on large-area flexible substrates, enabling bendable and foldable displays. Full-color micro-LED displays typically incorporate QD color conversion layers, leveraging their high PL quantum yield^{140,141}, wide color gamut, and superior color purity. Precise patterning of QDs onto blue micro-LED arrays via R2R or stamp transfer techniques enables high-efficiency full-color emission. Despite its significant potential, R2R processing faces challenges in micro-LED manufacturing, particularly regarding spatial error control and high-precision

alignment. The combination of high-speed operation and dynamic deformation of flexible substrates complicates real-time monitoring and in-line metrology¹⁴². Consequently, integrated approaches combining kinematic modeling with data-driven surrogate models are required to characterize and compensate for spatial alignment errors¹⁴³.

4.2.3 Fluidic Self-Assembly

Fluidic self-assembly (FSA) technology represents an innovative mass transfer solution for flexible devices, demonstrating exceptional compatibility with non-standard geometric chips (irregularly shaped chips) and flexible substrates. Its core principle involves designing the surface properties of chips and substrates to utilize interfacial forces, such as capillary action and vdW interactions, guiding micro-chips within a fluid medium to autonomously locate and precisely bind to pre-patterned receptor sites^{110,144}. LED chipsets must be epitaxially grown on separate wafers to achieve maximal device performance and subsequently transferred onto display substrates¹⁴⁵. Given the extraordinarily large number of LEDs required for transfer, a technology capable of assembling tens of millions of individual LEDs with low cost and high throughput is essential for the commercialization of micro-LEDs. For instance, a 50-inch ultra-high-definition display demands over 24 million chipsets smaller than 100 μm . Here we demonstrate a micro-LED illumination panel comprising over 19,000 disk-shaped GaN chipsets, each 45 μm in diameter and 5 μm in thickness, assembled within 60 s via agitation-based surface-tension-driven FSA, achieving a yield of 99.88%.

Owing to the low inertia of the chipsets, the fabrication of such sub-100 μm platelets with high yield at scale has long been regarded as a formidable challenge. The key insight to overcome this obstacle maybe the discovery that adding a small amount of poloxamer to the assembly solution increases its viscosity, thereby enhancing momentum transfer between the liquid and the platelets. As illustrated in Fig. 4.4a, a

schematic of the dip-coating process and the assembly sequence depicts the selective formation of solder joints on gold patterns across the substrate. The work in Fig. 4b represents an advance toward the ultimate goal of realizing low-cost, high-throughput manufacturing of full-colour micro-LED displays via FSA¹¹³. Furthermore, FSA enables simultaneous assembly of multiple micro-chips, substantially enhancing production efficiency, which is a critical advantage for manufacturing micro-LED displays requiring the integration of millions to billions of micro-chips^{75,146}. For instance, the research by Seongkyu Cho *et al.* demonstrated that FSA could precisely assemble over 19,000 GaN micro-chips (45 μm diameter) with a yield exceeding 99.90% within one minute¹¹². This method offers material- and size-agnostic advantages for inorganic semiconductor devices, applicable to micro-chips of diverse materials and dimensions. Fig. 4.4c depicts a fluid-assisted self-aligned transfer process for micro-LED chips developed by Young Rag Do *et al.* Chips dispersed in a solvent are deposited onto the target substrate via spray coating. An alignment rod sweeps across the deposited chips at constant speed and pressure, facilitating their alignment. The combined action of solvent flow and rod sweeping promotes correct alignment while expelling solvent between the smooth chip surfaces and substrate to enable robust bonding. This process continues iteratively until all chips are correctly aligned and bonded, filling all available sites. By optimizing conditions such as solvent selection, high-yield alignment of 259,200 micro-LED chips on a periodic interlayer can be achieved¹⁴⁷. FSA achieves sub-micron precision self-alignment by engineering hydrophobic-hydrophilic patterns on substrates and leveraging capillary forces. Research by Myeongho Park *et al.*¹⁴⁸ significantly reduced mis-assembly probability across multiple sites by optimizing receptor site spacing, further improving assembly yield. To enhance assembly efficiency and alignment accuracy beyond capillary forces, FSA can incorporate external forces such as acoustic focusing and wave energy. Acoustic focusing and magnetic forces enable precise control over micro-chip orientation and positioning within the solution, while wave energy-assisted FSA enhances rapid and accurate micro-chip arrangement.

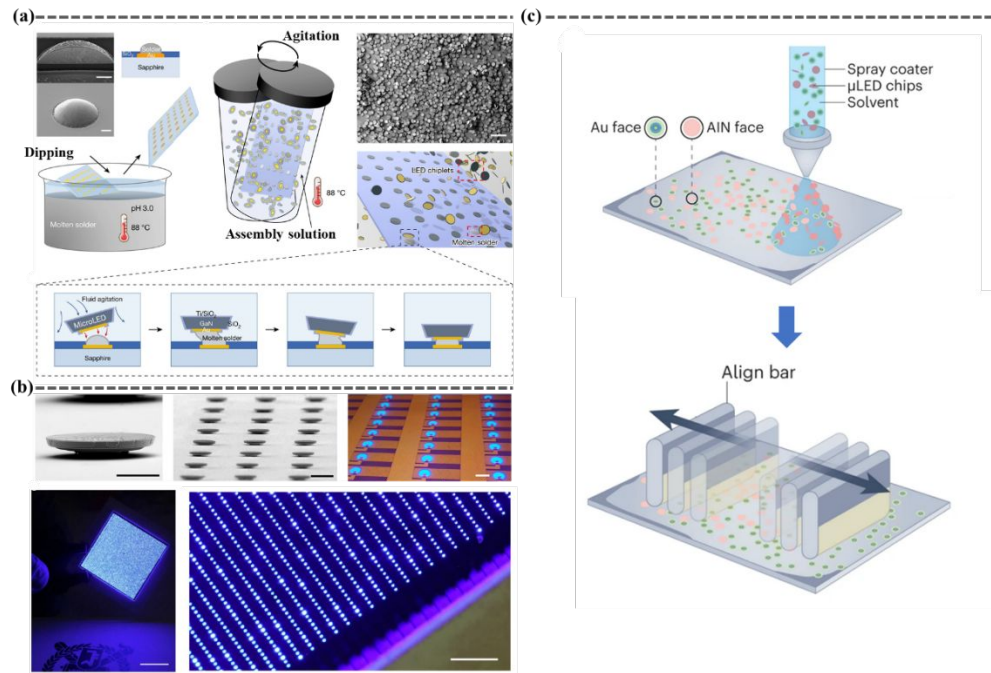


Fig. 4.4 (a) Fabrication of a micro-LED lighting panel by FSA. (b) Micro-LED lighting panel manufactured by a simple agitation-based FSA process.¹¹³ Copyright © 2023, Springer Nature. (c) Schematic showing the fluidic-assisted transfer system consisting of a micro-LED chip dispenser and align bar.¹⁴⁷ Copyright © 2023, Springer Nature.

Compared to traditional serial pick-and-place techniques, FSA employs batch processing, enabling chip self-alignment and self-assembly, particularly advantageous for small-sized LED chips. Unlike laser lift-off or pick-and-head technologies in mass transfer, FSA accomplishes transfer through fluid flow and spontaneous chip binding. Monolithic integration represents an alternative micro-LED fabrication strategy, directly integrating micro-LED arrays onto driving backplanes to achieve large-scale parallel assembly, significantly enhancing efficiency and throughput while enabling large-area parallel integration^{110,149}. The driving force for fluidic self-assembly (FSA) is the minimization of interfacial free energy. Receptor sites on the target substrate are patterned with hydrophilic or hydrophobic surface chemistry (*e.g.*, solder-wettable metal pads), while the micro-chips have complementary surface properties. When suspended in a fluid medium, the chips experience capillary forces upon approaching a receptor site. The formation of a liquid meniscus between the chip and the receptor

creates a negative Laplace pressure that pulls the chip into precise alignment. The binding energy is determined by the surface tension of the liquid, the contact angle, the geometry of the chip and receptor¹⁵⁰. For optimal assembly, the kinetic energy of the chip (imparted by agitation or flow) must be less than the capillary binding energy to ensure stable capture. Recent advances incorporate viscosity control additives (*e.g.*, poloxamer) to enhance momentum transfer from the fluid to the chips, improving assembly yield. Acoustic or magnetic forces can also be applied to overcome kinetic barriers and orient asymmetric chips.

Despite its considerable potential in manufacturing flexible chips, FSA technology faces challenges requiring further refinement. Regarding yield and uniformity, while laboratory demonstrations achieve high yields, ensuring precise alignment and uniform distribution across all chips to prevent voids or misplacement, remains a critical challenge for large-scale production. Variations in surface properties between micro-LED chips (differing materials and sizes) and substrates may impact assembly efficiency and quality, necessitating tailored surface treatment optimization¹⁴⁸. Furthermore, realizing full-color flexible micro-LED displays requires precise integration of red, green and blue chips. Current FSA research primarily focuses on monochromatic chip assembly, effective mixed-color chip assembly and integration of color conversion layers (*e.g.*, QDs) demand deeper investigation^{111,151}. Finally, persistent economic considerations warrant attention: although FSA may reduce per-chip assembly costs, developing and maintaining high-precision, large-scale FSA equipment potentially involves substantial initial investment and technical complexity.

5. Integrated Technologies for Chips

While the previous sections have detailed the design and performance of individual flexible GaN-based devices, ranging from micro-LEDs and photodetectors to lasers and synaptic units, their practical deployment in functional systems critically depends on the ability to integrate these discrete components onto a common platform. Integrated chips offer substantial advantages over standalone discrete devices, including reduced system footprint and parasitic inductance, lower power consumption, enhanced signal integrity and superior thermal management¹⁵². By consolidating multiple functions onto a single chip or a heterogeneously integrated module, such as light emission, photodetection, signal processing and power management, system-level complexity is significantly reduced while overall performance and reliability are improved. These integration-driven benefits have become increasingly essential as flexible GaN-based optoelectronics evolve from laboratory prototypes toward practical applications in wearable displays, biomedical implants and intelligent sensing systems¹⁵³.

5.1 Backplane and Substrate Materials

The backplane and substrate materials are critical enablers for flexible and high-performance micro-LED systems^{154,155}, and have recently been extended to GaN-based integrated platforms including photodetectors, laser arrays and neuromorphic devices, underscoring their role in chip-level heterogeneous integration. Consequently, material development is increasingly directed toward achieving simultaneous mechanical compliance, electrical stability and long-term reliabilities¹⁵⁶. In flexible micro-LED architectures, the backplane functions not only as a mechanical support but also as an active matrix for signal routing and pixel addressing, while emerging functional backplanes further incorporate sensing and signal-processing capabilities. However, stable operation under repeated mechanical deformation remains a key challenge.

Thin-film transistor (TFT) arrays constitute the dominant backplane technology, among which oxide semiconductors, particularly indium gallium zinc oxide (IGZO), have emerged as leading candidates due to their high mobility, low leakage and process uniformity^{157,158,159}. Low-temperature polycrystalline silicon (LTPS) and organic TFTs (OTFTs)¹⁶⁰ provide alternative trade-offs in performance and flexibility. LTPS TFTs provide an alternative route for ultra-high-performance backplanes owing to their exceptionally high mobility ($>290 \text{ cm}^2/\text{V}\cdot\text{s}$)¹⁶¹, enabling superior current driving for high-brightness micro-LEDs (Fig. 5.1a). Flexible LTPS-based displays maintain stability under 10^5 bending cycles and have been demonstrated in 9.4-inch 228 PPI and 12.1-inch 169 PPI full-color panels with contrast ratios exceeding 10^6 and brightness up to 700 nits^{20,162}. These characteristics make LTPS particularly suitable for AR/VR micro-displays and high-speed photonic systems¹⁶³.

IGZO-based backplanes have enabled multiple high-performance flexible displays, including an 8-inch mini-LED device ($<0.2 \text{ mm}$ thickness, $>60\%$ transmittance) and active-matrix micro-LED displays exceeding $10,000 \text{ cd/m}^2$ with ~ 130 PPI resolution (Fig. 5.1b). Full-color IGZO-driven systems further achieve pixel pitches below 0.55 mm and 256 grayscale levels, typically adopting 2T1C pixel circuits for stable current control^{157,158,164}. Beyond device demonstrations, IGZO performance has been improved through density engineering¹⁶⁵, doping and interface control. Sputtering optimization yields mobilities of $8.05 \text{ cm}^2/\text{V}\cdot\text{s}$ with 1.25 V threshold voltage²⁰, while Hf-doped multi-channel structures and rapid photonic annealing further enhance carrier transport and defect suppression¹⁶⁶. Encapsulation strategies using hybrid inorganic/organic barriers reduce threshold voltage drift to $<1.5 \text{ V}$ under 1000 h high-temperature and humidity stress. Nevertheless, hydrogen diffusion-induced instability and large-area uniformity remain unresolved challenges¹⁶⁷.

Amorphous silicon (a-Si) remains widely used in mature display systems due to low cost but limited mobility. Organic TFTs offer low-temperature and mechanically

compliant processing (<200 °C) but suffer from low carrier transport. Emerging 2D materials such as MoS₂ and graphene provide atomic-scale thickness and flexibility, while Fig. 5.1c compares their processing temperature windows and integration compatibility.

Substrate engineering is equally critical for mechanical and thermal stability. Polyimide (PI) remains the most widely adopted substrate due to its thermal robustness and compatibility with IGZO and LTPS TFTs^{168,169}, enabling flexible devices with thicknesses below 0.2 mm and transmittance above 60%. PEN and PET are widely used polymer alternatives, while PDMS enables extreme stretchability¹⁷⁰, with reported strain exceeding 100% in micro-LED arrays (Fig. 5.1d)¹⁷¹. Ultrathin glass (UTG) offers superior flatness and thermal stability despite its intrinsic brittleness, whereas metal foils provide excellent thermal and electrical conductivity for high-power GaN laser systems but are limited by optical opacity¹⁷². Comparative performance in bending radius, stretchability and resolution is summarized in Fig. 5.1e, while Fig. 5.1f highlights system-level multifunctional integration enabled by site-selective, anisotropically conductive integration (S-ACI) architectures.

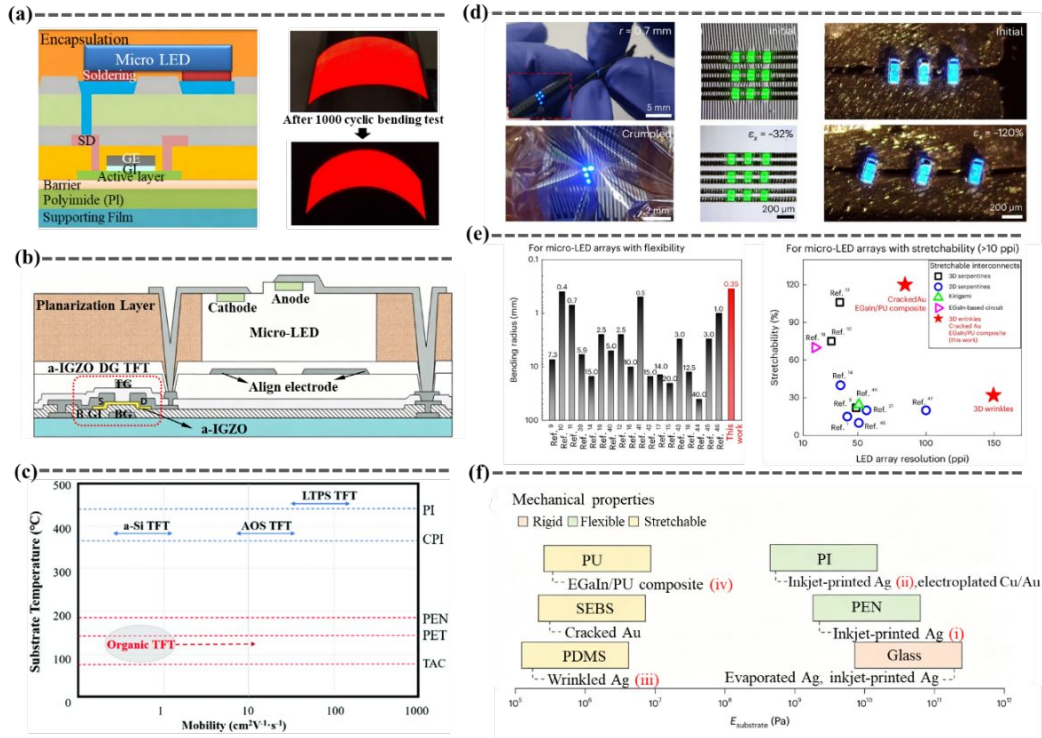


Fig. 5.1 (a) The structure of flexible LTPS TFT backplane with micro- LEDs.²⁰ Copyright © 2021, Society for Information Display. (b) Cross-section view of active matrix micro-LED display with dual-gate IGZO TFT.¹⁸ Copyright© 2020, The Society for Information Display. (c) Comparison of the maximum substrate temperature for processing different TFT technologies.⁹ Copyright © 2021, RSC publishing. (d) Photographs of micro-LEDs onto PEN and PI substrates. (e) Comparisons of bending radius, stretchability and resolution of LED array with previous studies. (f) Schematic of the demonstrated platforms through S-ACI.¹⁷¹ Copyright © 2024, Springer Nature.

Overall, progress in flexible GaN-based chips is tightly coupled to advances in backplane and substrate engineering¹⁷³. Despite substantial improvements, key limitations persist in mechanical endurance under extreme deformation¹⁷¹, thermal management, surface uniformity and heterogeneous integration. Recent demonstrations of ultra-flexible GaN-based arrays operating at bending radii of $\sim 0.7 \text{ mm}$ define current mechanical limits²⁴. Future directions are expected to focus on hybrid substrate architectures, improved encapsulation strategies and integration with emerging 2D materials for next-generation flexible GaN-based systems.

5.2 Integration Architectures for Flexible Chips

5.2.1 Heterogeneous Integration

Heterogeneous integration represents a key technological pathway for realizing high-performance flexible GaN-based chips. It effectively addresses lattice mismatch and thermal expansion incompatibilities between dissimilar materials, making it a cornerstone for advanced flexible electronic systems¹⁷⁴. In recent years, transfer printing has emerged as one of the most critical techniques for GaN device heterogeneous integration. Rogers and co-workers pioneered deterministic transfer methods based on elastomeric stamps, enabling the precise assembly of inorganic microscale devices onto flexible and stretchable substrates¹⁷⁵. Building on this foundation, Ahn *et al.* further developed micro-transfer printing approaches, significantly improving transfer yield and scalability, thereby enabling large-area and high-density integration of GaN device arrays¹⁷⁶. More recently, Lee and co-workers have extended transfer printing strategies to integrated photonic systems, demonstrating multifunctional integration of light-emitting, sensing and detection components within compact platforms.

At the system level, heterogeneous integration of GaN-based micro-devices with Si-based CMOS circuits has become a major research focus. Jeong *et al.* reported a high-resolution active-matrix micro-LED display system by integrating GaN emitter arrays with Si driving electronics, achieving high brightness and efficiency. This work highlights that the key challenge of heterogeneous integration lies not only in optimizing individual device performance, but also in achieving high-density interconnects and coordinated system operation. In addition, Ahn and co-workers demonstrated flexible optoelectronic systems that integrate light emitters and photodetectors, enabling combined imaging and sensing functionalities on deformable

substrate¹⁷⁶.

Beyond transfer printing, wafer bonding represents another important strategy for GaN heterogeneous integration. Jaeyong Jeong *et al.* systematically reviewed bonding approaches for integrating GaN with Si platforms (Fig. 5.2a), emphasizing their advantages in achieving large-area and uniform device integration¹⁵. Furthermore, Michinobu Tsuda *et al.* demonstrated that low-temperature bonding techniques can be employed to integrate GaN devices onto flexible substrates while avoiding thermal damage to polymer materials¹⁷⁷. In conjunction with release technologies discussed in Section 4.1, such as LLO and electrochemical lift-off, heterogeneous integration can be further enabled by high-quality GaN membrane transfer. Haruki Tsuchiya and co-workers developed an integration process for LED micro-displays targeting (Fig. 5.2b) augmented reality (AR) applications, and presented the demonstration of a blue monochrome active-matrix LED micro-display fabricated using this approach¹⁷⁸. One of the primary fabrication challenges in realizing such LED micro-displays is achieving pixel-level heterogeneous integration between III-V compound LEDs and Si CMOS circuits at a fine pixel pitch¹⁷⁹.

At the system level, heterogeneous integration is also driving the development of multifunctional optoelectronic systems. Yuanmin Luo *et al.* showed that integrating GaN devices with synaptic components enables optoelectronic neuromorphic systems capable of sensing, memory and processing of optical signals within a single platform²². Fig. 5.2c illustrates a three-in-one image sensor based on a multifunctional p–n diode architecture. In addition, closed-loop visual systems integrating micro-LEDs and photodetectors are emerging as promising architectures for flexible electronic skins and intelligent robotic systems. Despite these advances, several challenges remain. The yield and throughput of large-scale device transfer continue to limit practical applications. As device dimensions shrink, increasingly stringent requirements are imposed on alignment accuracy and interfacial defect control. Moreover, thermal

management and mechanical reliability in multi-device integrated systems remain critical concerns.

Looking forward, heterogeneous integration is expected to evolve toward high-throughput, high-precision and system-level co-optimization. Emerging approaches such as self-aligned transfer, advanced low-temperature bonding and multi-material integration strategies will further enhance system performance. With the continued expansion of GaN-based devices in optoelectronics, sensing and neuromorphic computing, heterogeneous integration will play a central role in next-generation flexible optoelectronic systems.

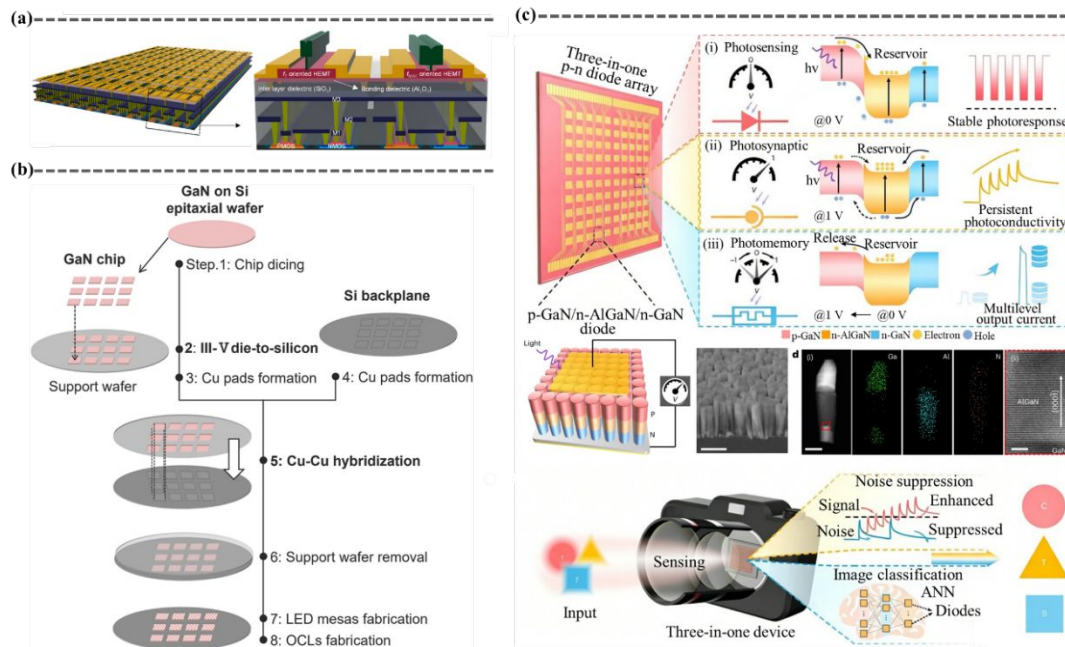


Fig. 5.2 (a) Heterogeneous and monolithic 3D integration of III-V devices on Si CMOS circuits.¹⁵ Copyright © 2022, American Chemical Society. (b) Process architecture of LED micro-displays.¹⁷⁸ Copyright © 2025, Society for Information Display. (c) Three-in-one image sensor based on a multifunctional p-n diode architecture.²² Copyright © 2026, Springer Nature.

5.2.2 Monolithic Integration

Monolithic integration demonstrates considerable potential for realizing full-color micro-LED displays by integrating multi-color emissive units or color conversion layers onto a single substrate, aiming to streamline manufacturing processes and enhance display performance. The advancement of this technology is crucial for meeting the escalating demands of high-end display applications for ultrahigh resolution, flexible and transparent displays, such as smart wearables, augmented reality/virtual reality (AR/VR) headsets and glasses-free 3D projection. The core principle of monolithic full-color micro-LED displays leverages semiconductor material properties to directly achieve RGB emission on a single chip, or to generate full-color output by exciting color conversion materials with blue micro-LEDs. Primary technical approaches include MQW heterogeneous integration and heterogeneous integration combined with color conversion techniques.

The MQW heterogeneous integration technique enables single-chip full-color emission by growing (In,Ga)N/GaN MQWs with varying compositions and thicknesses on a single epitaxial wafer, facilitating emission across different wavelengths¹⁸⁰. For instance, distinct MQWs such as $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}/\text{GaN}$ and $\text{In}_{0.55}\text{Ga}_{0.45}\text{N}/\text{GaN}$ (Fig. 5.3a) exhibit tunable emission spectra under varying injection currents. As shown in the I - V characteristics (Fig. 5.3b), injection currents of 20 μA , 5 and 50 mA at bias voltages of 1.95, 3 and 5 V correspond to RGB emission from the micro-LED pixel. This indicates that adjusting the injection current modulates the peak emission wavelength, enabling color control and broad-spectrum multi-wavelength emission from 450 to 620 nm through carrier injection regulation. Fig. 5.3c and 5.2d further illustrate the current-dependent EL spectra of micro-LEDs under injection currents ranging from 0.02 to 120 mA, alongside the spectral intensity ratio of the two MQW types measured via top and bottom emission¹⁴. This MQW heterogeneous integration significantly reduces the complexity associated with traditional mass transfer, lowering manufacturing costs and

process difficulty. Fabricating all emissive units on a single chip enables higher pixel density and superior pixel pitch uniformity. However, different growth windows and optimization conditions for MQWs emitting distinct wavelengths pose challenges: achieving efficient and stable RGB emission within a monolithic framework remains a critical research focus.

Alternatively, heterogeneous integration combined with color conversion utilizes GaN-based micro-LEDs as excitation sources alongside QDs or phosphors to partially convert blue light into green and red emission, enabling full-color displays. Notably, (In,Ga)N blue/green dual-color micro-LED arrays can be monolithically realized on MOCVD-grown GaN-on-Si epitaxial wafers and heterogeneously integrated with AlGaInP red micro-LED arrays^{181–183}. Combined with a CMOS backplane, this forms a full-color micro-display prototype. Fig. 5.3e depicts the fabrication pathway for such a prototype based on (In,Ga)N/AlGaInP heterogeneous integration, achieving a pixel density of 391 PPI¹⁸⁴. This approach leverages the high efficiency of blue micro-LEDs and the maturity of GaN materials, while capitalizing on the superior optical properties of novel color conversion materials like QDs, such as high quantum yield and narrow emission spectra, to achieve wide color gamut and high color saturation.

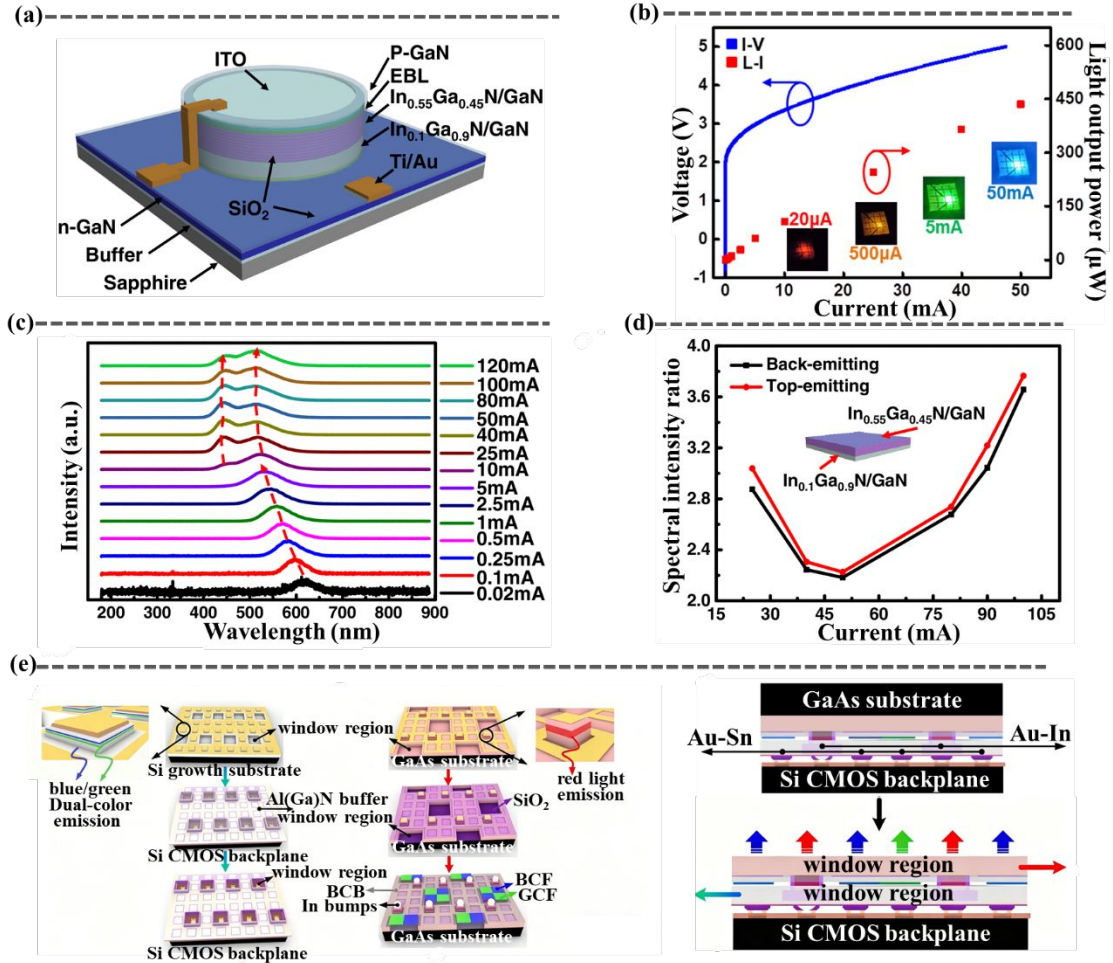


Fig. 5.3 (a) Schematic illustration for the top-emitting micro-LED with a pixel diameter of 80 μm . (b) I - V and L - I characteristics of the 80- μm -diameter micro-LED array. In the inset, micro-LED pixels with different emission colors corresponding to different injection currents. (c) Current-dependent EL spectra of the micro-LED at various injection currents from 0.02 to 120 mA. (d) Ratio of spectral intensity of two types of MQWs tested by top and back emitting.¹⁴ Copyright © 2024, Optica Publishing Group. (e) Process flow of the double-layer thin-film full-color micro-display by heterogeneous integration.²⁶ Copyright © 2023, Springer Nature.

5.3 System-Level Functional Integration

From a system-level perspective, GaN-based material platforms (including (In,Ga)N,

(Al,Ga)N, and GaN heterostructures) have evolved beyond conventional optoelectronic devices toward multifunctional integrated chip systems. These systems integrate optical emission, signal detection and neuromorphic computation within a unified epitaxial and circuit framework. The core concept of GaN integration is not limited to device optimization, but rather the co-design of emissive layers, functional interfaces and electronic driving backplanes, enabling cross-layer coupling between photons and carriers. Within this framework, micro-LEDs, photodetectors and synaptic devices can be understood as different functional manifestations of a unified GaN system architecture^{185–187}.

5.3.1 GaN Emission System

At the device implementation level within GaN emission systems, (In,Ga)N-based LEDs and micro-LED arrays represent the most mature technology for high-resolution optoelectronic integration^{188,189}. As application requirements extend toward AR/VR displays and wearable electronics, full-color emission becomes a key system-level requirement. Representative full-color integration strategies include RGB tri-chip architectures and QD-based wavelength conversion systems (Fig. 5.4a-c)^{190,191,192,193,194}. In RGB integration, red, green and blue micro-LED chips are independently fabricated and assembled onto a common backplane to form pixelated emissive arrays. Typically, (In,Ga)N materials are used for blue and green emission, while AlGaInP is employed for red emission due to epitaxial limitations¹⁹⁶. These heterogeneous chips are transferred and integrated through mass transfer techniques and aligned onto CMOS or TFT backplanes, forming high-density emissive matrices. However, from a system-level perspective, RGB-based architectures suffer from scalability limitations arising from mass transfer yield, alignment precision and defect control^{188,195}. As pixel density increases, these constraints become dominant bottlenecks in manufacturability and yield, limiting large-area commercialization.

In contrast, QD-based wavelength conversion architectures decouple emission generation from color rendering. In this system, a blue or UV GaN micro-LED array serves as a unified excitation backplane, while QD or phosphor layers define the final emission spectrum¹⁹⁶. This decoupled architecture significantly simplifies pixel integration and reduces heterogeneous material complexity^{197–199}. Following advances in CsPbX₃ perovskite QDs, halide engineering (Cl/Br/I) has enabled tunable full-color emission across the visible spectrum^{200,201,202}. Patterning techniques such as inkjet printing, photolithography and elastomer-assisted transfer have been widely explored to achieve spatially resolved color conversion (Fig. 5.4d). Additionally, distributed Bragg reflectors (DBR) have been introduced to enhance optical extraction efficiency and suppress back-reflection losses^{197,203–207}. Fig. 5.4e illustrates the photolithographic fabrication process of a colour-converted micro-quantum-dot LED (QLED) panel reported by Yuyu Jing, which combines blue micro-QLED electroluminescent devices with red and green QD colour converters (QDCCs). A pre-patterned template is fabricated via photolithography and subsequently employed as a substrate for patterning blue micro-QLED devices, thereby achieving an ultrahigh pixel resolution of up to 6350 pixels per inch²⁰⁸. Nevertheless, complete suppression of unconverted blue emission remains challenging, indicating that optical management is a fundamental system-level constraint rather than a material-level issue^{209,210}.

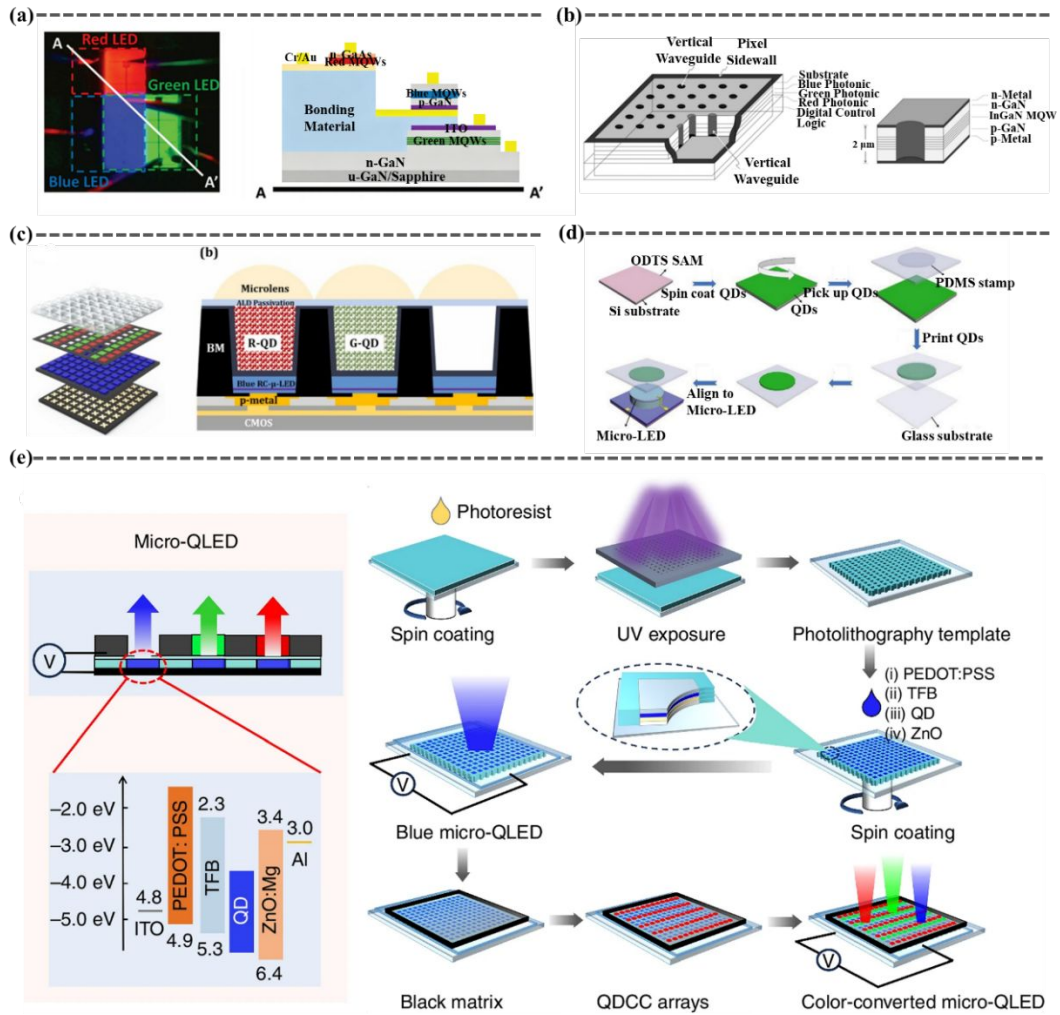


Fig. 5.4 (a) Full-color subpixels of luminescence microscopy images of horizontal structures.¹⁹⁴ Copyright © 2021, Wiley-VCH GmbH. (b) Quantum photonic imager (QPI) pixel structure with stacked RGB active layers and vertical waveguides.¹⁹³ Copyright © 2015, The Society for Information Display. (c) The schematic and close-up view of the proposed high-resolution, high-brightness full-color micro-LED display¹⁹⁵. Copyright© 2024, Elsevier (d) Schematic of transfer printing QDs to combine with micro-LEDs.²¹¹ Copyright © 2023, IEEE. (e) Photolithographic fabrication of high-resolution micro-QLEDs towards color-conversion microdisplay.²⁰⁸ Copyright © 2025, Springer Nature.

5.3.2 GaN Sensing Systems

Beyond emission functionality, GaN-based heterostructures enable integrated photodetection and self-powered sensing systems. (Al,Ga)N-based UV photodetectors and GaN heterostructure phototransistors have been widely investigated owing to their intrinsic wide-bandgap properties and high radiation stability. Recent advances have demonstrated the remarkable potential of GaN-based sensing architectures in high-performance photodetection and spectral imaging. Sun and co-workers reported the first miniaturized UV spectrometer and spectral imager based on a novel GaN cascaded photodiode architecture. As illustrated in Fig. 5.5a²¹², the device operates across the 250–365 nm range, achieves a spectral resolution of ~0.62 nm, and exhibits a sub-10 ns response time, thereby establishing a new performance benchmark for on-chip spectral sensing. Deep neural network algorithms further enable high-accuracy spectral reconstruction and spatially resolved imaging of organic substances. Complementing this system-level advance, high-sensitivity GaN UV photodetectors integrated with graphene have also been demonstrated, wherein the unique 2D/3D heterointerface enhances responsivity.

Beyond conventional photodetection, a breakthrough avalanche-like UV photomultiplication phenomenon has been recently triggered in ultrathin amorphous/crystalline GaN heterostructures. Fig. 5.5b presents the device schematic, while Fig. 5.5c shows the architecture diagram, a photograph of the imaging system printed circuit board, together with imaging results of the letter “U”. This detector achieves a responsivity exceeding 10^7 A/W, surpassing commercial photomultiplier tubes by one to two orders of magnitude, while maintaining an ultralow dark current below 1 pA. The architecture overcomes the long-standing trade-off between high gain and low dark current that has constrained conventional avalanche photodiodes, thereby opening a new paradigm for on-chip ultrasensitive UV detection¹⁰.

In the domain of biochemical sensing, (Al,Ga)N/GaN HEMTs have emerged as powerful platforms for label-free and ultra-sensitive detection. Fig. 5.5d illustrates the schematic of a recently reported graded-barrier (Al,Ga)N/GaN MOS-HEMT biosensor featuring dual nanocavity sensing regions. When employed for SARS-CoV-2 detection, the device exhibits pronounced threshold voltage shifts and drain current modulation, enabling recognition through both dielectric and charge-modulation mechanisms. In a complementary approach, a genetically engineered bacterial S-layer protein is integrated onto an (Al,Ga)N/GaN HEMT sensor, achieving ultrasensitive detection of tumour antigens with 100% diagnostic accuracy for ovarian cancer across a dynamic range spanning 10^{-21} to 10^{-14} M²¹³. Relative to conventional chemical crosslinking, the S-layer-driven assembly increases antibody loading by 50% and substantially suppresses non-specific adsorption in complex biological environments²¹³.

At the system level, GaN sensing architectures rely on the co-integration of optical excitation, carrier transport and electrical readout circuitry. A compact multifunctional sensing system combining a monolithic GaN optoelectronic chip with an elastic optical fibre structure has been demonstrated, capable of simultaneously measuring angle, tension and impact force²¹². It is a configuration that exemplifies the trend toward chip-scale, multi-parameter sensing platforms for motion detection, robotics and human-machine interfaces. More importantly, emerging system architectures enable the unification of emission and detection within a single GaN platform, allowing self-sensing or feedback-enabled optoelectronic systems. Nonetheless, key challenges remain, including suppression of dark current, spectral selectivity and crosstalk between emission and detection channels when co-integrated on the same chip.

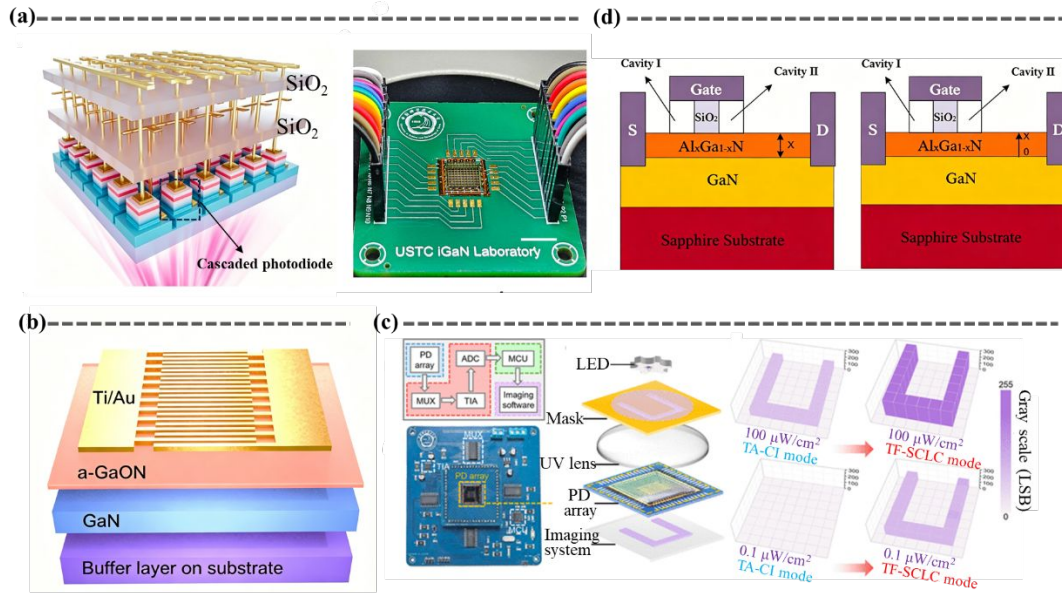


Fig. 5.5 (a) A schematic illustration of a fabricated miniaturized spectral imager chip and a photograph of the wire-bonded chip on the printed circuit board.²¹² Copyright © 2025, Springer Nature. (b) Schematic structure of the fabricated GaON/GaN device. (c) Architecture diagram and photograph of the imaging system.¹⁰ Copyright © 2026, The American Association for the Advancement of Science. (d) Schematic of MOS-HEMT with conventional (Al,Ga)N barrier.²¹³ Copyright © 2025, Elsevier.

5.3.3 GaN Neuromorphic and Computing Systems

GaN-based heterostructures also provide a promising platform for neuromorphic and in-memory computing applications. By leveraging carrier trapping/detrapping dynamics, polarization fields and optoelectronic coupling effects, GaN devices can emulate synaptic behaviors such as STP and LTP²¹⁴. A significant advance in this direction is the development of GaN-nanowire-based artificial synaptic devices. We demonstrated a three-terminal GaN nano-synapse enabled by a dielectrophoretic-assisted assembly strategy that ensures controllable nanowire placement within 10 minutes, which is a cost-efficient method that addresses the critical challenge of precise nanowire alignment. The device exhibits robust and gate-tunable synaptic plasticity, including STM-LTM transition, PPF and spike-timing-dependent plasticity, with gate

modulation enhancing postsynaptic current by over 1,000% and achieving recognition accuracy exceeding 95% in a spiking neural network (SNN). In parallel, Jianya Zhang *et al.* reported an electric-stimulated controllable synaptic GaN nanodevice using the same dielectrophoretic alignment technique, achieving 95% recognition accuracy after only 13 training cycles and demonstrating image denoising capability. These results highlight the promise of three-terminal nano-synapses as effective and cost-efficient building blocks for next-generation neuromorphic systems⁹⁵.

Beyond purely electrical stimulation, GaN photoelectrochemical synapses offer a pathway toward bio-realistic neuromorphic functionality. Liu *et al.* reported a photoelectrochemical synaptic device based on p-(Al,Ga)N/n-GaN semiconductor nanowires that incorporates chemical-electric synaptic behavior, which is a feature absented in conventional optoelectronic synapses⁹⁶. By implementing closed- or open-circuit conditions, the device switches between STP and LTP, while chemical modifications to nanowire surfaces amplify synaptic responses through tuning of external and internal charge behaviors. Notably, under varied electrolyte environments, the device successfully mimics chemically-regulated synaptic activities and emulates oxidative stress-induced biological phenomena, bridging the gap between classic optoelectronic synapses and biological synapses.

Monolithic integration of photodetection and neuromorphic computing within a single GaN device represents another transformative direction. Min Jiang *et al.* designed a dual-mode transparent device based on a graphene/(Al,Ga)N nanowire heterojunction that monolithically integrated self-driven 360° photodetection with artificial synaptic functionality. At 0 V bias, the device functions as a fast-response self-driven photodetector; upon applying bias, it switches to a synaptic mode that successfully emulates PPF, STP, LTP and learning/forgetting behaviors. The device achieves an exceptionally high UV/visible rejection ratio of 1.29×10^4 , an ultralow dark current below 1 pA. The energy consumption per synaptic event is only 2.5×10^{-14} J, which is

comparable to synaptic processes in the human brain. Leveraging its long-memory characteristics, the device has been successfully applied to guide humanoid robots in performing direction discrimination and motion learning⁶².

At the system level, neuromorphic implementation requires coordinated integration of device arrays with programmable driving circuits, enabling spatiotemporal encoding of optical or electrical signals. Unlike conventional CMOS-based neuromorphic systems, GaN-based architectures offer intrinsic advantages in high-speed operation and optoelectronic compatibility. However, challenges remain in achieving stable multi-state retention, energy-efficient weight modulation and large-scale array uniformity.

Overall, GaN-based integrated systems represent a unified multifunctional platform spanning optical emission, photodetection and neuromorphic computation. These subsystems share a common architectural foundation based on epitaxial materials, device structures and electronic backplanes. Future development will likely focus on monolithic GaN integration and GaN–CMOS heterogeneous co-design, *etc.*

6. Applications

The inherent mechanical flexibility, high optoelectronic performance and biocompatibility of GaN-based devices have opened up a wide spectrum of application scenarios that go far beyond conventional rigid electronics. This chapter provides a comprehensive overview of the representative and emerging applications of flexible GaN-based devices and chips. We begin with high-resolution displays (Section 6.1), followed by wearable and implantable medical devices (Section 6.2), brain–computer interfaces (Section 6.3), artificial synapses for neuromorphic computing (Section 6.4), multifunctional integrated systems (Section 6.5), and finally discuss potential future applications (Section 6.6). Collectively, these examples illustrate how the fundamental materials, device and integration technologies discussed in previous sections translate into practical systems, while also highlighting remaining challenges and future directions toward real-world deployment.

Nevertheless, not all of the above-mentioned applications are equally poised for immediate commercialization. Flexible GaN-based displays for wearable devices (smartwatches, augmented reality glasses) and flexible lighting have benefited greatly from the maturing mass-transfer technologies and well-established LTPS/IGZO backplane integration, placing them on a clear trajectory toward market entry within the coming few years. Flexible UV photodetectors for wearable health monitoring, such as sunburn alert or wound healing assessment, are similarly close to large-scale application. In contrast, implantable optogenetic probes and spinal cord stimulators (Sections 6.2 and 6.3) still face stringent requirements for long-term biocompatibility and hermetic encapsulation. Brain–computer interfaces based on GaN micro-displays are likely to appear first in clinical intraoperative monitoring before any consumer-oriented adoption. Looking further ahead, self-powered and imperceptible neuromorphic computing skins (Sections 6.4 and 6.5) that integrate sensing, memory and actuation remain at the fundamental research stage, as well as other potential

applications (Section 6.6).

6.1 Display Applications

In recent years, flexible GaN-based LEDs have achieved substantial progress in display applications. Leveraging the superior optoelectronic properties, high stability and long operational lifetime of GaN, together with advances in flexible substrate technologies^{215,216}, GaN-based flexible displays are rapidly transitioning from laboratory demonstrations to early-stage commercialization. These systems show strong potential in emerging applications such as wearable electronics, AR/VR near-eye displays^{217–219}, automotive displays and human–machine interfaces²²¹. This section summarizes recent advances from three perspectives: device-level performance breakthroughs, system integration and functional expansion, and innovations in substrates and materials^{183,222–224}.

A longstanding challenge for GaN-based micro-LEDs lies in efficiency degradation at reduced device dimensions. When chip sizes shrink below $\sim 5\ \mu\text{m}$, non-radiative recombination, particularly at sidewalls, becomes dominant, leading to a significant drop in external quantum efficiency (EQE). In 2025, a joint team reported a highly efficient flexible red micro-LED with a diameter of only $1.5\ \mu\text{m}$, achieving a peak EQE of 6.5% at a wavelength of 649 nm²²⁴. This performance is enabled by an ultrathin ($\sim 1\ \text{nm}$) epitaxial AlN passivation layer, deposited via argon plasma-assisted atomic layer deposition (ALD), which forms a single-crystalline coating on the micro-LED sidewalls and effectively suppresses non-radiative recombination pathways (Fig. 6.1a). Compared with conventional passivation materials such as HfO_2 or Al_2O_3 , the AlN-treated devices exhibit a ~ 2.5 -fold enhancement in PL intensity. For flexible implementation, the micro-LED array is flip-chip bonded onto a polyimide (PI) substrate, followed by controlled interfacial adhesion to enable “peel-free” removal of the Si substrate. The resulting device, with a thickness below $20\ \mu\text{m}$, maintains stable

emission under repeated bending. As illustrated in Fig. 6.1b and 6.1c²²⁵, such devices enable concepts such as flexible micro-LED displays integrated into electronic contact lenses. The combination of a 1.5 μm pixel size and 6.5% EQE satisfies the requirements for ultrahigh-resolution displays ($>5,000$ PPI), providing a viable pathway for near-eye displays in emerging immersive environments.

In parallel, significant progress has been made in large-area flexible displays. For instance, Seok-Lyul Lee *et al.* demonstrated a 9.4-inch flexible micro-LED display with a resolution of 228 PPI¹⁶⁸. Chan-Jui Liu and co-workers developed a 14.6-inch rollable micro-LED display (202 PPI) capable of withstanding 10,000 bending cycles at a bending radius of 5 mm, with less than 5% brightness degradation²²⁶. Under similar conditions, OLED counterparts typically exhibit image retention and luminance non-uniformity. Chung-Yuan *et al.* reported a 7.1-inch flexible micro-LED display with a peak brightness exceeding 2,000 nits, a viewing angle greater than 160° and color performance exceeding 90% of the BT.2020 standard²²⁷. The device withstands up to 100,000 bending cycles with an inner bending radius of 10 mm, exhibiting negligible degradation (brightness variation $<1\%$ and color shift <0.001). These results collectively highlight the strong potential of flexible micro-LEDs for foldable and deformable display systems.

According to the extreme scaling limit, Polar Light Technologies has demonstrated sub-micro-LEDs based on a proprietary pyramidal architecture, achieving device dimensions down to ~ 500 nm without conventional etching processes. The company presented its micro-display prototype in 2025, which is targeting initial commercialization²²⁸. Meanwhile, Aledia has pursued an alternative route based on 3D GaN nanowire-on-Si technology, introducing the FlexiNova micro-LED platform with chip dimensions of $15\ \mu\text{m} \times 30\ \mu\text{m}$ fabricated on 200 mm Si wafers. Commercial production at operating voltages around 9 V has been achieved as of 2026, marking an important milestone in micro-LED industrialization²²⁹.

At the device level, novel flexible LED architectures have also been explored. A team reported a method for fabricating flexible GaN-based vertical LEDs using a soft transparent substrate formed from cured photosensitive resin combined with a single-substrate transfer process²³⁰. The resulting devices exhibit double-sided emission, with S-shaped electrodes enhancing mechanical flexibility. The study further reveals that the emission characteristics under bending are governed by the piezo-phototronic effect, whereby polarization charges at the (In,Ga)N/GaN MQW interfaces modulate the band structure, leading to shifts in emission wavelength and intensity. This insight provides new design opportunities for flexible displays and wearable human-machine interfaces.

Beyond conventional display functionality, The rapid development of artificial intelligence (AI) and high-performance computing (HPC) has imposed unprecedented demands on data transmission systems. Conventional interconnect technologies struggle to keep pace with the exponential growth in computing requirements. Researchers at CEA-Leti are exploring an innovative solution: developing GaN-based micro-LEDs and micro-photodetectors for short-distance chip-to-chip optical communications (Fig. 6.6d). This technology leverages manufacturing processes originally developed for micro-display applications, offering a viable path toward massively parallel, energy-efficient data transmission systems²³¹. The high brightness of micro-LEDs allows sufficient space for integrating photodetectors within the display panel, enabling additional functionalities such as imaging, gesture recognition and biometric sensing. The study also systematically analyzed crosstalk effects as a function of emitter-detector spacing, providing key design guidelines for integrated systems. Similarly, a research team developed GaN-based integrated sensing-display devices featuring low power consumption, high transparency and multifunctionality. By employing nanowire structures instead of planar films, the devices achieve ~20% enhanced optical absorption and reduced energy consumption²³². Furthermore, the integration of MQWs and QDs enables multiband emission and detection, while a wet-

etch-based flexible film formation process yields highly transparent (>80%) and mechanically robust films capable of 360° bending. These advances highlight a transition toward display–sensing integration in intelligent interactive systems.

In terms of system integration, heterogeneous 3D integration of GaN emitters with Si CMOS driver circuits remains a critical challenge. Efficient integration across disparate material systems is essential for enabling high-performance near-eye display technologies, particularly in AR/VR applications (Fig. 6.1e)²¹. In 2026, Suzhou HanHua Semiconductor Co., Ltd. established an 8-inch GaN-on-Si micro-LED manufacturing platform compatible with standard CMOS processes, incorporating proprietary damage-free Si removal and full-process integration from epitaxy to micro-display fabrication. As early as 2025, the company achieved mass production of hybrid bonding with a 3.75 μm pitch and yields exceeding 95%, providing a robust foundation for high-density micro-display manufacturing. At the flexible system level, advanced packaging technologies have also played a key role. For example, a team employed flexible fan-out wafer-level packaging (FOWLP) to heterogeneously integrate approximately 100,000 GaN micro-LEDs with CMOS drivers onto a PDMS substrate. By incorporating adaptive lithography to compensate for device displacement during PDMS processing, they have realized a passive-matrix-driven flexible micro-LED display with high yield and scalability^{233–235}.

Overall, these advances demonstrate that flexible GaN-based display technologies are rapidly evolving from device-level innovations to system-level integration and multifunctional platforms. Continued progress in materials engineering, transfer technologies and heterogeneous integration will be essential to fully unlock their potential in next-generation display and interactive systems.

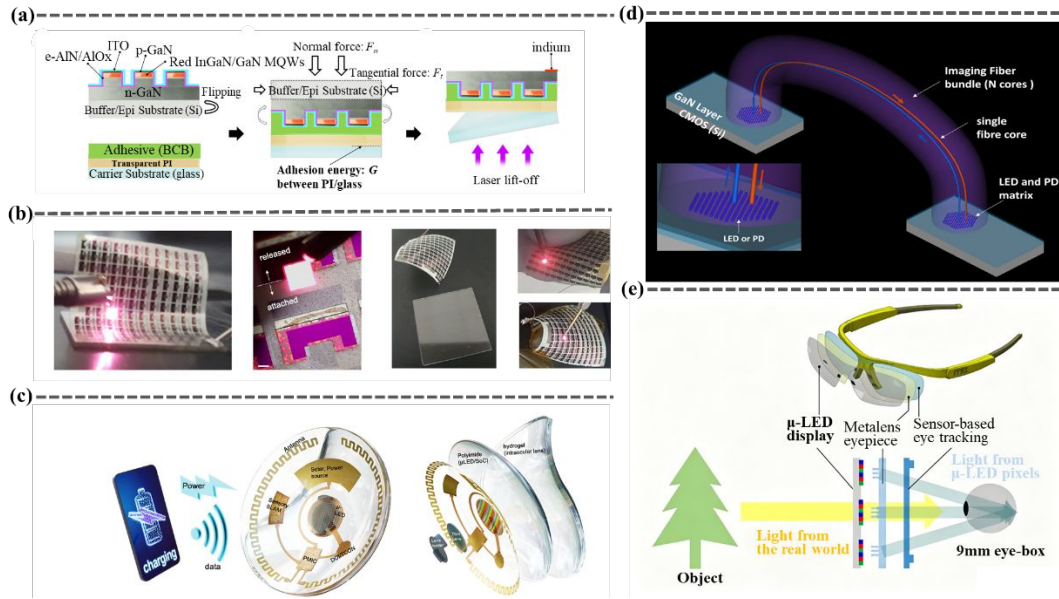


Fig. 6.1 (a) Schematic of fabrication flow. (b) Operation of flexible red micro-LEDs in the middle of the release step. (c) Photograph images of flexible red micro-LEDs operating under fully flexible forms.²²⁵ Copyright © 2025, Springer Nature. (d) Communication system composed of two matrices of GaN micro-LED and micro-photodetectors via an imaging fiber bundle.²³¹ Copyright © 2024, Wiley. (e) The conceptual illustration of a novel see-through optical module on the AR device.²¹ Copyright © 2023, IOP.

6.2 Medical and Health Applications

With the continuous enhancement of public health awareness, the market for wearable health monitoring devices has exhibited explosive growth. Flexible micro-LEDs, owing to their advantages of ultra-high brightness, low power consumption, compatibility with flexible substrates, biocompatibility and highly integrated design, have demonstrated significant application potential in this field^{25,71,236–238}. For instance, Jianan Niu's team developed a fully flexible, integrated electronic display skin by integrating flexible micro-LEDs, stretchable circuits and a zinc/polyacrylamide/vanadium pentoxide hydrogel battery pack (Fig. 6.2a)²⁵. Using a vapor-phase collective transfer method, 10,000 micro-LEDs can be efficiently and precisely transferred onto a flexible substrate,

ensuring high flexibility (thickness of only 240 μm) and ultra-thin characteristics. The paired flexible hydrogel battery pack provides sustainable energy with a specific capacity of 331.3 mAh/g. This skin display combines excellent stretchability and biocompatibility, conforming to body movements while maintaining high-resolution dynamic visual output, laying the groundwork for advanced skin-implantable displays and promising transformative applications in information interaction, healthcare and artificial intelligence²⁵.

Claudia Kathe's team developed a soft, stretchable carrier capable of conforming to the dura mater of the spinal cord, integrating micro-LEDs (Fig. 6.2b)¹⁷. The silicone-phosphor matrix coating covering the micro-LEDs provides both mechanical protection and light conversion functions, compatible with a large library of opsins. It is a lightweight head-mounted wireless platform powers the micro-LEDs and performs low-latency on-chip processing of perceived physiological signals to enable closed-loop optical stimulation control. This device reveals the roles of various neuron subtypes, sensory pathways and supraspinal projections in motor control in both healthy and spinal cord-injured mice¹⁷. Ming Li's team pioneered a red-blue dual-wavelength independent regulation system: red light (630 nm, 10.3 mW/cm²) promotes mitochondrial function, while blue light (470 nm, 42.1 mW/cm²) enables rapid sterilization. Their wearable red LED patch and spray F-gel combination therapy ensures a temperature rise of <5°C during 30-minute continuous operation via PDMS encapsulation, meeting long-term wear safety standards. It supports precise power/duration control via a mobile app and integrates real-time temperature sensor alerts (automatic power-off above 42°C), constructing a treatment-monitoring-protection integrated home solution. With a small size, 3-hour battery life and a cost of only 20% that of hospital devices, this flexible micro-LED patch enables phototherapy for skin conditions (*e.g.*, acne and psoriasis), wound healing, inflammation reduction and antibacterial infection through targeted wavelength illumination²³⁸.

Jae Hee Lee's team developed a wearable surface-mount micro-LED photo-stimulator for skincare and aesthetics (Fig. 6.2c). It comprises a light diffusion layer, 900 thin-film micro-LEDs and PDMS, achieving uniform surface illumination (100% luminous efficiency) within a $2 \times 2 \text{ cm}^2$ area. With uniform irradiation, high flexibility and thermal stability, the surface-mount micro-LED maximizes photo-stimulation effects on the skin surface. In vitro (human skin equivalent models, HSEs) and in vivo (mouse dorsal skin) experiments validate its inhibitory effect on melanogenesis (Fig. 6.2d). Compared to traditional LED stimulators, the surface-mount micro-LED significantly reduces melanin content, tyrosinase activity and microphthalmia-associated transcription factor (MITF) levels²³⁹.

Beyond medical applications, aesthetic dermatology represents another key area. Hair loss, a modern issue involving aesthetic, psychological and social dimensions, is conventionally treated with laser-induced skin stimulation, which suffers from high energy consumption, bulky equipment and limited daily use. Min Seo Kim's team developed a face-conforming micro-LED mask for anti-aging skin care (Fig. 6.2e). This mask achieves deep tissue treatment via close-range light irradiation, with its 3D origami structure adapting to complex facial contours for tight adhesion. Using blister-assisted laser transfer technology, micro-LEDs are transferred with high throughput (50 chips/second) and precision, facilitating large-area processing for scalable production. Clinical trials demonstrate significant improvements in elasticity, laxity and wrinkles across six facial regions, with the deep skin elasticity around the mouth exceeding that of traditional LED masks by 340%²⁴⁰. Photodynamic therapy (PDT) is a promising strategy that promotes antitumor immunity by inducing immunogenic cell death (ICD) in tumor cells. However, practical PDT applications are limited by the shallow light penetration depth and the use of intense visible light, which triggers immunosuppression in tumor tissues. Jiwoong Choi *et al.* proposed an implantable microscale micro-LED-guided PDT that can activate photosensitizers deep in vivo on demand with weak visible light irradiation, thereby enhancing antitumor immunity (Fig.

6.2f and 6.2g)²⁴¹. Han Eol Lee's team developed a wearable photo-stimulator for hair growth using high-performance flexible red vertical micro-LEDs (Fig. 6.2h)¹⁹. Through a simple monolithic fabrication process, they successfully fabricated micro-LEDs with high light output ($\sim 30 \text{ mW/mm}^2$), low forward voltage ($\sim 2.8 \text{ V}$) and excellent flexibility, which were suitable for wearable bio-stimulation. In experiments, the high-performance red micro-LEDs, leveraging high thermal stability, device uniformity and mechanical durability, achieved hair-growth stimulation in alopecia mice, significantly improving hair loss symptoms (Fig. 6.2i). Photo-biomodulation therapy based on GaN-based micro-devices also holds significant potential in the aesthetic industry¹⁹.

Flexible micro-devices can also be integrated into biosensors for monitoring physiological signals or biomarkers. For example, they can serve as indicator lights or micro-displays in flexible wearables for heart rate, blood oxygen saturation or glucose monitoring. Through opto-electro-thermal multi-modal sensing and millisecond-scale closed-loop control, Claudia Kathe's team developed a flexible GaN-based biosensors to achieve precise regulation of the entire spinal cord in freely behaving animals, providing dynamic intervention tools for neural circuit analysis and laying a foundation for clinical implantable devices with its biocompatible design¹⁷.

In summary, flexible GaN-based micro-devices, leveraging their unique advantages in biocompatibility, integration and multi-modal functional regulation, have demonstrated cross-disciplinary application value in wearable health monitoring, phototherapeutic devices and aesthetic medicine. Although current research has overcome key technical bottlenecks in device fabrication, energy management and biosafety, further exploration is needed in long-term implant stability, multi-organ coordinated monitoring and intelligent closed-loop therapy. In the future, by constructing an integrated network of biosensing-phototherapeutic intervention-health assessment and combining flexible electronics with edge computing technology, flexible GaN-based micro-devices are expected to drive wearable devices from single-function monitoring

to proactive health management, providing innovative solutions for precision medicine and personalized health services. With the evolution of flexible electronics, they may further integrate micro-devices to achieve non-invasive optical diagnostics, playing a role in precise light regulation for implantable medical devices (e.g., neural stimulation, optogenetics research or in vivo photodynamic therapy).

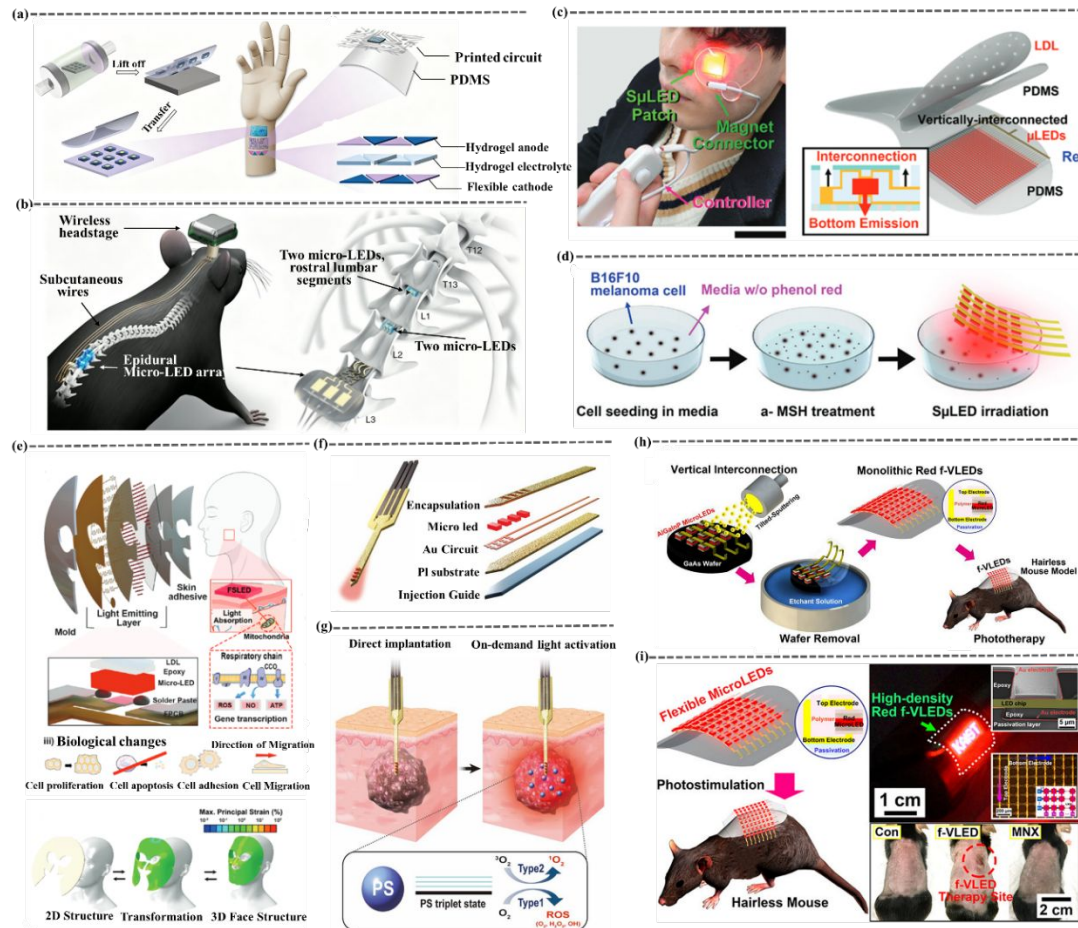


Fig. 6.2 (a) Preparation of the flexible micro-LED display.²⁵ Copyright © 2024 , Wiley. (b) Schematic overview of the optoelectronic system, including a zoom on the insertion of the micro-device array over the epidural surface of the spinal cord.¹⁷ Copyright © 2021, Springer Nature. (c) A photograph of surface-mount micro-LED patch prototype which is operated on the human face. (d) Conceptual illustration of the in vitro cell experiment confirm the anti-melanogenic effect of themicro-devices.²³⁹ Copyright © 2022, Wiley. (e) Overall concept of face-fit surface-lighting micro-LEDs mask.²⁴⁰ Copyright © 2024, Wiley. (f) The micro-LED is prepared by stacking micro-scale

LEDs fabricated on a PI substrate and transferred onto an injection guide, which is designed as a needle-like structure with polysiloxane acrylate. (g) The micro-device is directly implanted into the core part of the tumor tissues, followed by irradiation with visible light.²⁴¹ Copyright © 2022, Springer Nature. (h) Schematic illustration of the fabrication procedure and trichogenic photo-stimulation by monolithic flexible AlGaInP vertical LEDs. (i) Conceptual illustration of trichogenic photo-stimulation via monolithic red f-VLEDs and photographs of mouse dorsal skin in control and MNX-treated groups after 20 days of hair-regrowth experiments.¹⁹ Copyright © 2018, American Chemical Society.

6.3 Brain-computer Interfaces

GaN has demonstrated considerable promise for biomedical implantation, with multiple studies confirming its biocompatibility and non-toxicity. The investigations have reported that GaN remains non-toxic and biocompatible both before and after peptide functionalization, positioning it as an attractive candidate for bioelectronic interfaces^{22,23,121}. Further validation confirms the absence of cytotoxicity of GaN toward PC12 cells, a model system that recapitulates neuronal behavior, thereby furnishing critical evidence for the safe deployment of GaN in neural implants. Flexible GaN nanowires, characterized by a high aspect ratio and mechanical compliance far exceeding that of rigid Si-based materials, can conform intimately to soft brain tissue^{123,247}, substantially mitigating mechanical trauma during insertion. Moreover, as a wide-bandgap semiconductor, GaN possesses exceptional chemical stability, resistance to acidic and alkaline environments²⁴², and inherent radiation hardness, all of which are advantageous for long-term implantation within the complex physiological milieu *in vivo*.

Optogenetics, a powerful modality for selective neuronal control, necessitates implantable optical neural probes capable of delivering light with precision to deep

brain regions. However, external optical pathways are hampered by tissue scattering and absorption, limiting access to subcortical structures. Furthermore, closed-loop optogenetic experiments demand co-localized optical stimulation and electrophysiological recording on a single probe. Addressing these requirements, the team of Maysam Chamanzar reported a monolithically integrated flexible optoelectronic neural probe wherein GaN micro-LED arrays and recording electrodes are co-embedded within a compliant polymer substrate fabricated via wafer-scale micromachining. The probe employs Parylene C as both substrate and insulation layer, capitalizing on its biocompatibility, mechanical flexibility and optical transparency. Up to 32 micro-LEDs ($22 \times 22 \mu\text{m}^2$) integrated per shank emit blue light at 445 nm and deliver an output power exceeding 200 μW at 2 mA, which are suited for Channelrhodopsin-2 (ChR2) activation. Crucially, the double-sided probe architecture permits simultaneous optical stimulation and electrophysiological recording from both anterior and posterior surfaces, thereby enabling closed-loop interrogation of neural circuits with high spatiotemporal resolution (Fig. 6.3a)²⁴⁶.

In the related work, the group of Hiroto Sekiguchi reported a hybrid probe integrating multi-point GaN-based micro-devices with neural recording electrodes. The devices achieve localized optical stimulation and simultaneous neural signal acquisition via direct bonding of GaN micro-LEDs to electrode sites²⁴⁷. Validated in a murine brain model, the system demonstrates selective neuronal activation with minimal thermal perturbation. The thin-profile micro-LED probe reduces invasiveness while preserving excellent optical performance. As shown in Fig. 6.3b, the team has developed micro-LED neural probes fabricated on GaN-on-Si epitaxial wafers, investigating brain function while avoiding implantation-induced cerebral damage²⁴⁷.

Intraoperative functional brain mapping during neurosurgery constitutes a critical challenge. Conventional approaches often rely on disparate teams and equipment, constraining real-time visualization of eloquent cortex and risking inadvertent resection

of healthy tissue. A breakthrough reported by the Shadi Dayeh group describes a flexible GaN micro-display that measures and displays cortical surface potentials in real time at a refresh rate of 40 Hz (Fig. 6.3c)²⁴⁷. This device couples a platinum nanorod electrode grid with a GaN LED array on an ultrathin polymer film, integrating 2,048 micro-LEDs to combine high-resolution neural recording with instantaneous visual feedback. Its conformal design accommodates the complex curvature of the cortical surface, offering neurosurgeons a direct means to delineate functional regions. Fig. 6.3d captures real-time mapping of the boundary between primary motor and somatosensory cortices on the porcine cortical surface. Fig. 6.3e illustrates the display of electrical potentials evoked by direct electrical stimulation (DES) on the cortical surface. The high efficiency and low power consumption of GaN LEDs ensure bright light output even under ambient surgical illumination while generating negligible heat, thereby averting thermal injury to brain tissue. In rodent and porcine models, the system successfully enabled real-time demarcation of the M1/S1 border, local identification of cortical columns and dynamic monitoring of epileptiform pathological activity²⁴⁸.

Beyond optical stimulation and electrophysiology, the integration of GaN-based artificial synapses into brain-computer interface (BCI) systems offers a pathway toward local, on-chip processing and learning of neural signals, thereby circumventing the architectural bottleneck of conventional BCIs that rely on external computational units. Despite these substantial advances in flexible GaN-based BCI devices, several challenges impede translation to large-scale clinical application: (i) longitudinal studies are required to rigorously assess long-term *in vivo* stability and biocompatibility; (ii) efficient heterogeneous integration with mature CMOS signal-processing platforms remains a technological hurdle; (iii) the reliability of synaptic and sensor performance under cyclic mechanical deformation in flexible GaN devices warrants systematic evaluation; (iv) wireless power delivery and data telemetry schemes must be further optimized to meet the stringent power and bandwidth requirements of fully implantable systems. Looking forward, continued improvements in GaN material quality and micro-

/nano-fabrication techniques, in concert with advanced neural coding algorithms and closed-loop neuromodulation strategies. They are poised to propel GaN-based flexible neural interfaces from laboratory prototypes to transformative clinical applications in brain function restoration, neurological disease diagnosis and therapy, and neural prosthetic control.

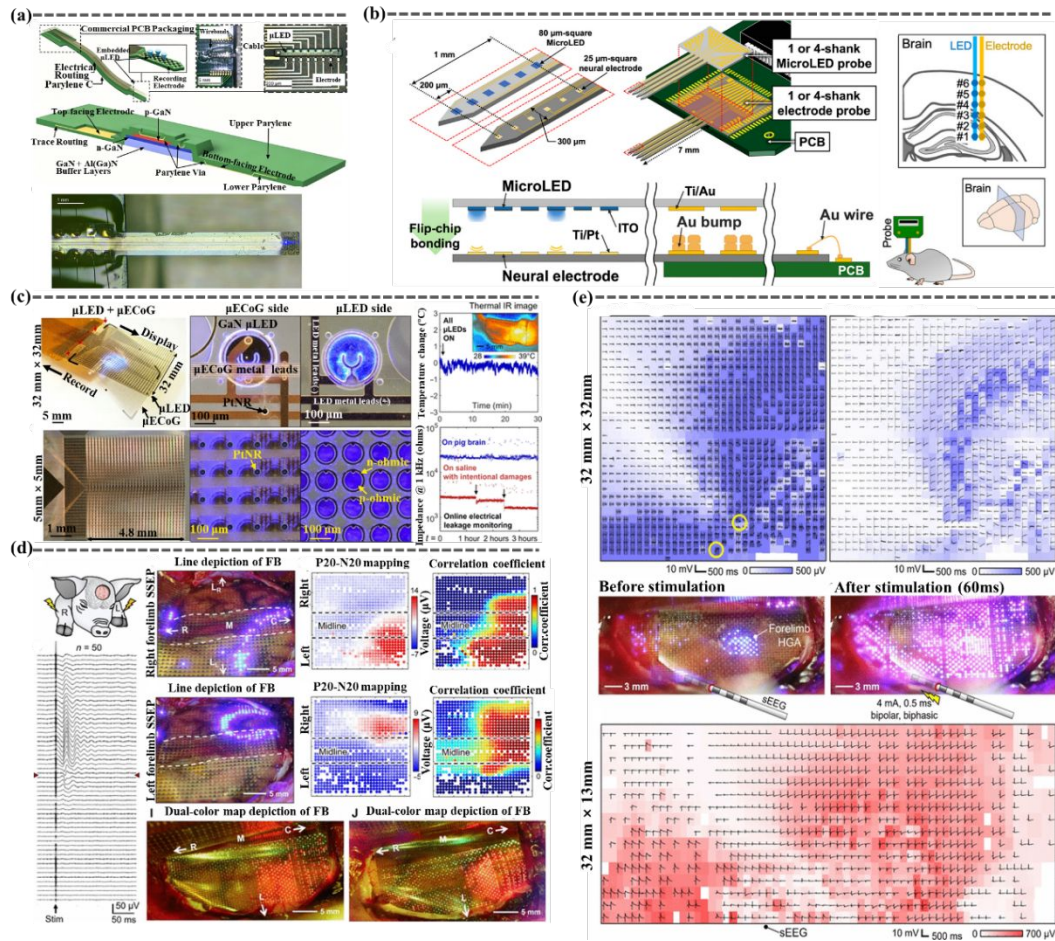


Fig. 6.3 (a) Dense arrays of collocated micro-devices and recording electrodes.²⁴⁶ Copyright © 2021, Frontiers. (b) Schematic of the hybrid device integrating micro-LEDs and neural electrodes, and light stimulation using the hybrid probe in a mouse model.²⁴⁷ Copyright © 2025, IOP science. (c) Fabrication process and safety evaluation of the micro-display. (d) Real-time mapping and display of the borders on the cortical surface of pig brains. (e) Display of electrical potentials in response to DES on the cortical surface of pig brains.²⁴⁸ Copyright © 2025, Science.

6.4 Application of Artificial Synapses

In recent years, GaN-based artificial synaptic devices have garnered significant attention owing to their burgeoning potential in neuromorphic computing and intelligent sensing systems (Fig. 6.4a and 6.4b). Thanks to the intrinsic wide bandgap, strong polarization effects and exceptional environmental stability of GaN, these devices offer distinct advantages in optoelectronic neuromorphic platforms, particularly for applications demanding robust stability, noise immunity and precise optical modulation. Integration with flexible substrate technologies further enables the realization of bendable and conformable intelligent systems, thereby paving a crucial technological pathway for next-generation wearable electronics and bio-integrated devices²⁴⁴.

Functionally, GaN-based synaptic devices have demonstrated the capability to faithfully emulate key biological synaptic behaviors, including STP, LTP, STDP and learning-forgetting dynamics. These properties facilitate direct hardware implementation of neural networks wherein synaptic weights are dynamically modulated by either electrical or optical stimuli. In stark contrast to conventional von Neumann computing architectures, such devices support in-memory computing paradigms, markedly reducing the energy and latency overhead associated with data shuttling and thereby exhibiting substantial advantages in energy-efficient computation²⁴⁹. From a mechanistic perspective, exemplified by the GaN-based photoelectrochemical synapse (Fig. 6.4b), the synaptic response arises from a synergistic interplay between internal optoelectronic processes and electrolyte-mediated electrochemical reactions. The surface band bending at the p -(Al,Ga)N nanowire/electrolyte interface opposes the built-in field of the internal p - n junction. This unique energetic landscape governs carrier dynamics: photogenerated electrons are preferentially extracted to the external circuit, generating a positive current spike, whereas holes accumulate transiently within the nanowire due to sluggish interfacial

redox kinetics. This accumulation modulates the potential barrier, culminating in a negative transient current spike upon light termination⁵³. This hole-storage effect, induced by opposing electric fields, constitutes the fundamental physical origin of the device history-dependent behavior and STP^{243,250,251}. An electrically controllable GaN nanowire synaptic device, fabricated via dielectrophoresis, directed assembly that enables precise nanowire positioning within 10 minutes²⁵². It successfully emulates key biological synaptic functions including PPF, spike-number-dependent plasticity (SNDP) and STDP, exhibiting pulse-parameter-tunable memristive responses at a threshold voltage of ~ 7 V.

In terms of applications, neuromorphic vision systems represent one of the most compelling demonstrations. By monolithically integrating GaN-based photodetectors with synaptic devices, systems capable of bio-inspired visual information processing can be constructed. Within this architecture, incident optical signals are not merely detected but directly transduced into synaptic weight modulations, enabling in-situ fusion of sensing, memory and processing that mimics early-stage biological visual functions such as edge detection and motion perception. Figure 6.4a delineates an integrated neuromorphic processing pipeline for vision-based drone navigation. The input layer fuses frame-based and event-based camera streams to concurrently capture static intensity information and dynamic motion cues. The neural processing layer emulates the highly parallel and recurrent connectivity of biological networks, leveraging a hybrid algorithmic approach that incorporates artificial neural networks (ANNs), SNNs and mixed architectures. These algorithms are deployed across conventional processors (CPUs/GPUs) and specialized neuromorphic hardware, including non-volatile memory-based in-memory computing (IMC) units, to efficiently execute critical visual tasks such as optical flow estimation, depth perception, semantic segmentation and object detection. When combined with flexible substrates, such systems can conform to curved or irregular surfaces, holding considerable promise for electronic skins and wearable visual sensors²¹⁴.

Beyond vision, GaN-based artificial synapses are garnering increasing interest for multimodal perception. Their responsiveness to optical, electrical and even mechanical stimuli (*e.g.*, piezo-phototronic effects) positions them as versatile sensory nodes capable of co-processing heterogeneous signals. In a flexible form factor, the integration of pressure sensors, photodetectors and synaptic devices provides a hardware foundation for real-time tactile-visual fusion in intelligent robotics and advanced prosthetics. In the realm of wearable and bio-integrated electronics, the chemical robustness and favorable biocompatibility of flexible GaN synaptic devices render them suitable for long-term operation in complex physiological environments. The coupling of neuromorphic processing units with biosensors enables in-situ analysis and real-time feedback of physiological signals, with profound implications for brain-machine interfaces and implantable diagnostic systems.

Furthermore, for edge computing and distributed intelligence, GaN-based neuromorphic devices facilitate local learning and inference, thereby reducing overall system power consumption and improving response latency. Their intrinsic resilience to radiation and thermal extremes further extends their operational envelope to harsh environments, including aerospace and industrial monitoring. Fig. 6.4c illustrates an application wherein a humanoid robot, guided by optical stimuli and operating under zero-bias (voltage mode), demonstrates motion learning capabilities. This implementation underscores the potential of dual-modal devices in enabling low-power, autonomous behavioral adaptation in robotic systems⁶². Integrating neuromorphic computing, photodetection and imaging functionalities within a single device remains a formidable challenge. To address this, we developed a dual-mode monolithic device based on an (Al,Ga)N nanowire/graphene heterojunction (Fig. 6.4d)²⁹.

Humanoid robotics is currently at a pivotal inflection point, transitioning from laboratory validation to large-scale commercial deployment. The year 2026 is widely

regarded as the first year of commercialization for humanoid robots. Tesla's third-generation Optimus V3 is expected to be launched in mid-2026²⁵³. The Fremont factory has already started constructing its first production line targeting an annual capacity of one million units, while the Texas plant is planning for a future capacity of ten million units per year²⁵⁴. Figure Ltd. has increased the production efficiency of its Figure 03 robot by 24-fold in less than 120 days, and the design of Figure 04 has already been finalized and is undergoing pre-production testing²⁵⁵. In China, Xpeng's Iron is scheduled to start mass production in the coming year. Unitree is advancing its IPO on the STAR Market²⁵⁶. The industry has shifted from pure technology validation to production capacity preparation, order fulfilment and cost control, placing unprecedented demands on autonomous perception, real-time decision making, energy-efficient processing and multimodal information fusion for humanoid robots²⁵⁷.

Looking ahead, the convergence between GaN synaptic devices and the humanoid robot industry is accelerating. From a sensing perspective, synaptic arrays with smaller pixel pitches and higher integration densities will gradually approach the resolution of the human retina, laying the hardware foundation for truly "eye-like" visual perception. From a computational perspective, monolithic sensing-in-computing architectures are expected to reshape the conventional "sensing-transmission-processing" pipeline of robot vision into a parallel framework where perception is computation, substantially reducing end-to-end latency and overall power consumption. From an industrial perspective, the miniaturization, high-temperature tolerance and radiation hardness of GaN chips have already been demonstrated in key robot components such as encoders and joint control systems. For instance, the first domestic GaN magneto-resistive encoder chip operates stably at 180 °C with an angular accuracy of $\pm 0.1^\circ$, meeting the demanding requirements of highly dynamic operation and precision assembly, thus removing key technical barriers for integrating synaptic devices into industrial systems²⁵⁸. As the number of degrees of freedom in humanoid robots continues to increase (Tesla Optimus already has nearly 50 DOF) and the richness of environmental

perception expands, the demand for edge-side sensing-computing integration will grow exponentially²⁵⁹. With their inherent advantages in low power consumption, high response speed and on-chip parallel processing, GaN artificial synaptic devices are poised to play an increasingly pivotal role in brain-inspired perception and intelligent control of humanoid robots.

Despite this promising outlook, the practical deployment of GaN-based artificial synapses faces several challenges. Key hurdles include the stability of multi-level conductance states, device-to-device variability essential for large-scale neural networks, and the long-term reliability of synaptic performance under cyclic mechanical deformation in flexible systems. Moreover, seamless heterogeneous integration with mature CMOS platforms remains a critical technological barrier to system-level implementation. Looking forward, advances in defect engineering, interface modulation and sophisticated heterogeneous integration strategies, coupled with the incorporation of emerging materials such as 2D layers or organic functional films, are poised to further enhance performance and uniformity. As flexible electronics, photonics and neuromorphic computing converge, GaN-based artificial synapses are well-positioned to serve as a cornerstone technology for constructing integrated intelligent systems capable of seamless perception, computation and response.

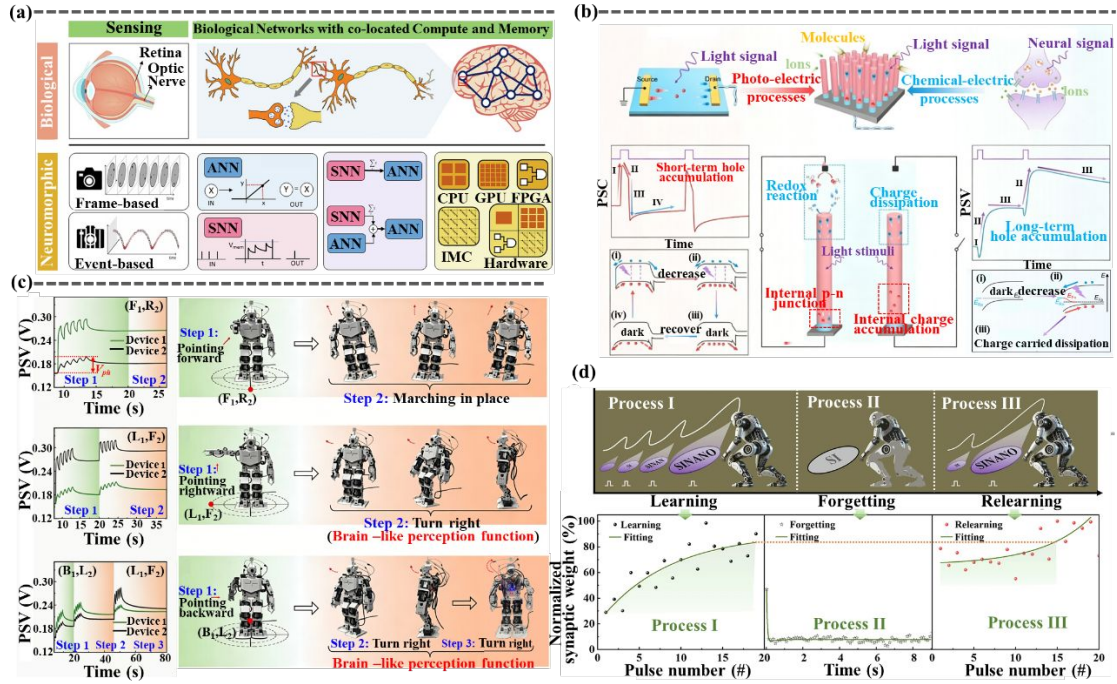


Fig. 6.4 (a) An integrated neuromorphic processing pipeline for vision-based drone navigation.²¹⁴ Copyright © 2025, Springer Nature. (b) Working mechanisms of the photoelectrochemical synapse.⁵³ Copyright © 2024, Springer Nature. (c) Motion learning of humanoid intelligent robots under optical stimulation at 0 A bias (voltage mode).⁶² Copyright © 2025, Springer Nature. (d) The schematic illustration and experimental results of the “learning-forgetting-relearning” processes.²⁹ Copyright © 2025, Springer Nature.

6.5 Application of Multifunctional Devices

As a wide-bandgap semiconductor, GaN has emerged as a cornerstone material for multifunctional devices owing to its exceptional electrical and optical properties, high thermal conductivity, large breakdown electric field and outstanding chemical stability. A defining intrinsic feature of GaN is its strong piezoelectric polarization, arising from the non-centrosymmetric wurtzite crystal structure along the c-axis, which imparts markedly distinct physical and chemical characteristics to the two polar faces of the wafer. Capitalizing on this unique polar asymmetry, a team introduced the concept of “dualtronics”, wherein optoelectronic devices are fabricated on the gallium-polar

face while electronic devices are realized on the nitrogen-polar face of the same GaN wafer²⁶⁰. This approach enables the simultaneous integration of photonic, electronic and acoustic functionalities within a single semiconductor platform, establishing a new paradigm for monolithic multifunctional integration and substantially elevating the functional density achievable on a single GaN chip.

Recent advances in flexible GaN multifunctional devices have further broadened their application horizon. Mechanical flexibility has been attained through diverse strategies: electrochemical selective etching to delaminate GaN thin films from rigid substrates for transfer onto flexible backplanes, embedding GaN nanowires within hydrogels to construct wearable photodetectors, and secondary substrate transfer techniques to integrate GaN micro-disks onto PDMS elastomers¹³⁵. These methodologies preserve the excellent optoelectronic attributes of GaN while endowing the devices with mechanical compliance, thereby laying a critical foundation for wearable and implantable multifunctional systems.

The monolithic integration of light emission and photodetection represents one of the most compelling manifestations of GaN multifunctionality. As reported developed a versatile three-terminal GaN-based diode by monolithically incorporating a third terminal, comprising a metal/ Al_2O_3 dielectric stack, onto a conventional p - n diode structure (Fig. 6.5a and 6.5b). This architecture permits agile switching between light-emission and photodetection operational modes. When configured as a light emitter, the three-terminal diode exhibits a broad intensity modulation range and an enhanced modulation bandwidth from 160 to 263 MHz. When functioning as a photodetector, the modulation of applied bias enables reconfigurable optoelectronic logic gates such as NAND and NOR²³. In parallel, p - n diodes based on (Al,Ga)N nanowires have demonstrated bias-controlled, dual-functional broadband photodetection and light emission on silicon platforms, offering a promising avenue for sensing, imaging and visualization in integrated photonics. Furthermore, we designed a multifunctionally

integrated GaN chip capable of combining detection, display and synaptic learning functionalities within a single platform (Fig. 6.5c). Fig. 6.5d showcases a proof-of-concept demonstration wherein a humanoid robot equipped with this chip executes the three integrated functions⁵⁸.

Piezotronics and piezo-phototronics constitute the core mechanisms enabling synergistic force–electricity–light coupling in GaN multifunctional devices. The intrinsic piezoelectric polarization of GaN permits mechanical stress to modulate carrier transport, thereby facilitating multi-physical co-sensing and actuation without reliance on an external power supply. As schematically depicted in Fig. 6.5e, the device innovatively exploits the piezo-phototronic effect to tune the QCSE within the $p-i-n$ quantum wells, markedly amplifying the modulation of photo-response by mechanical strain and enabling high-sensitivity discrimination of graded mechanical deformation.

At the chip-level multifunctional system scale, monolithic GaN integration schemes offer compelling technological advantages. A monolithic GaN optoelectronic system (MGOS) co-integrates an energy harvester, a LED, and a $\text{SiO}_2/\text{TiO}_2$ distributed Bragg reflector (DBR) on a single chip (Fig. 6.5e)²⁶¹. The DBR simultaneously functions as a waterproof encapsulation layer and an optical filter. This system operates stably in both boiling and ice water without external interconnects, demonstrating the capacity to receive encoded information from an external light source to convert it into electrical energy, and directly activate the LED for optical information relay. As illustrated in Fig. 6.5f, the MGOS is successfully adhered to a freely swimming crucian carp, achieving wireless energy harvesting and optical communication in an aquatic setting²⁶².

Monolithic integration schemes leveraging (In,Ga)N/GaN MQW diodes have further realized multifunctional optoelectronic sensor chips that combine light emission and detection, exhibiting considerable promise for industrial automation, biomedical diagnostics and environmental monitoring. GaN heterostructures, notably

(Al,Ga)N/GaN HEMTs, exhibit distinctive multifunctional potential in biochemical sensing. The high-mobility and high-density two-dimensional electron gas (2DEG) induced at the (Al,Ga)N/GaN interface by the confluence of spontaneous and piezoelectric polarization confers extreme sensitivity to surface charge perturbations, enabling rapid detection of diverse biochemical targets including proteins, DNA, kidney injury molecules, prostate cancer biomarkers, pH and mercury ions.

In the domain of wearable multifunctional sensing, a research team developed a dual-modal sensing platform based on a GaN micro-disk laser integrated on a PDMS flexible substrate (Fig. 6.5g)²⁶³. This platform achieves simultaneous high-precision detection of strain and refractive index, with a strain sensitivity of 0.08 nm/mm^{-1} , a refractive index sensitivity as high as 666.9 nm/RIU , and a detection limit of $5.4 \times 10^{-6} \text{ RIU}$. Complementary efforts combined a monolithic GaN optoelectronic chip with an elastic optical fiber structure to realize multi-parameter measurement of angle, tension and impact force, offering a cost-effective and miniaturized solution for motion tracking, robotics and human-machine interfaces²⁶³. Beyond these examples, emulating the mechanoreceptor functionality of human skin remains a central objective in wearable electronics. Aadil Waseem and co-workers reported a self-powered flexible piezoelectric sensor based on a GaN nanowire array with tunable conductivity, which successfully replicates the slow-adapting and fast-adapting mechanoreceptors of biological skin. The e-skin constructed from *n*-type and semi-insulating GaN nanowire arrays responds to both static and dynamic pressure stimuli²⁶⁴. The slow-adapting mechanoreceptor exhibits response and reset times of 11 and 18 ms, respectively (at 1 Hz), enabling complex tactile functions such as object grasping and surface texture discrimination.

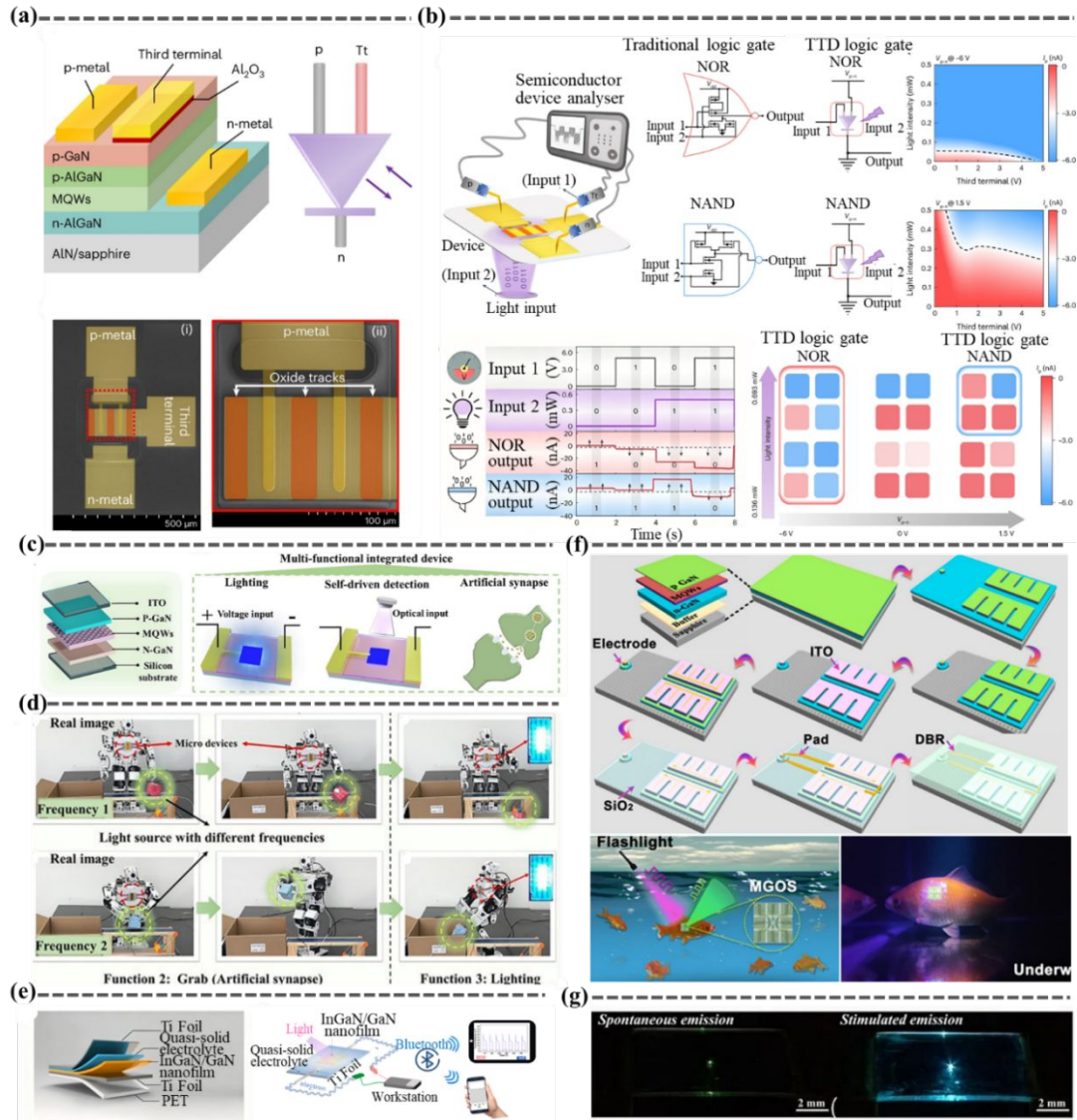


Fig. 6.5 (a) A three-terminal light emitting and detecting diode. (b) Implementation of three-terminal PDs for photodetectors.²³ Copyright © 2024, Springer Nature. (c) Schematic illustration of the device with three functions. (d) Applications of humanoid-robot learning.⁵⁸ Copyright © 2025, Elsevier. (e) Schematic of the prepared pin-PEC photodetector and the operating principle on the flexible PEC.²⁶¹ Copyright © 2025 Elsevier. (f) Profiles of waterproof MGOS and underwater optical wireless communication system.²⁶² Copyright © 2022, Springer Nature. (g) Dual-modal sensing platform based on flexible GaN micro-disk lasers on PDMS substrate.²⁶³ Copyright © 2025, Wiley.

6.6 Potential Applications

Building upon established applications in displays, biomedical monitoring, brain–computer interfaces, artificial synapses and multifunctional integration, flexible GaN-based devices and chips are now advancing into more frontier domains. A series of recent milestone developments clearly delineates the trajectory of this technology from discrete functional demonstrations toward system-level integration.

At the chip-level integration frontier, Intel Foundry reported the world’s thinnest GaN chiplet in 2025, achieving a Si substrate thickness of merely 19 μm on 300 mm GaN-on-Si wafers. As illustrated in Fig. 6.6a²⁶⁵, this work also charts the evolution of GaN point-of-load power solutions from discrete motherboard voltage regulators to GaN vertical power delivery and ultimately to GaN power chiplets, which is driven by escalating demands for power density and efficiency. By monolithically integrating GaN power transistors with Si-based digital control circuitry on a single die, this breakthrough enables the power chip itself to host complex computational functions, directly addressing the pressing requirements of modern electronic systems for higher power density, faster response and more compact form factors. Process reliability validation has already extended to data centers, 5G/6G infrastructure and satellite communications. Looking forward, embedding such GaN chiplets within flexible polymer substrates could provide the hardware foundation for distributed intelligence across curved surfaces, wearable textiles and soft robotic exteriors, with the modular architecture substantially lowering barriers to system customization and rapid prototyping.

In wireless communications, the radio frequency (RF) front-end technology stack for 6G is undergoing a pivotal materials transition. In 2026, Soitec (SOIT) and Nanyang Technological University jointly announced results from a four-year GaN-on-Si RF device research program, achieving power-added efficiency (PAE) exceeding 50%

under low-voltage conditions compatible with handset batteries²⁶⁶. These findings affirm the viability of GaN-on-Si for meeting the cost, scalability and integration density requirements of future mobile terminals. Concurrently, Xiaomi's RF team, in collaboration with Dynax Semiconductor and HKUST, presented a low-voltage GaN-on-silicon RF power amplifier tailored for mobile handsets in 2025. Through co-optimization of circuit design and semiconductor processing, the device attains a high PAE surpassing 80% and an output power density of 2.84 W/mm at a 10 V operating voltage, marking the first system-level validation of GaN HEMT technology in a mobile phone platform (Fig. 6.6b). These advances signal a clear trend: GaN is permeating from infrastructure toward terminals, and the introduction of flexible GaN membranes will further unlock integration advantages in conformal antenna apertures and volume-constrained modules²⁶⁷.

At the monolithic multifunctional integration level, on-chip synergy between photodetection and neuromorphic computing is overcoming the inherent timescale mismatch between rapid sensing and prolonged signal processing. In our previous work, we reported a GaN-based dual-mode transparent device wherein the deliberate introduction of surface defects coupled with localized contact interface engineering enables monolithic integration of fast photodetection (millisecond-scale response) with ultralow-power neuromorphic computation (second-to-minute-scale relaxation)¹². The device achieves a dynamic response range exceeding three orders of magnitude and has been validated in intelligent perception systems for humanoid robots. For the work of Chunshuang Chu and co-workers, they fabricated a GaN-based integrated optoelectronic device consisting of a phototransistor and a mini-LED. Fig. 6.6c shows its fabrication process, in which a polarization-gated phototransistor utilizes polarization-induced negative charges at the GaN/(Al,Ga)N interface to block current flow. Benefiting from the conductivity modulation effect of photogenerated carriers, the phototransistor allows current to flow upon UV excitation, which in turn enables the mini-LED to produce blue emission. Fig. 6.6d illustrates the principle of making

UV light visible by exciting the polarization-gate phototransistor to achieve energy transfer into GaN-based blue emission. Measurements show that without UV excitation, the integrated device exhibits an extremely low current (less than 1.4×10^{-4} mA) and negligible blue radiation from the mini-LED. Once illuminated by a 12.7 mW commercial 305 nm UV LED, the visible mini-LED shows a current level of 44.4 mA and an optical power of 81.1 mW. The visible blue radiation demonstrates the effectiveness of this GaN-based integrated optoelectronic device for UV alert applications. Notably, the device is a two-terminal structure with the polarization gate integrated internally, avoiding post-fabrication metal gate deposition. Moreover, it can be transferred onto flexible substrates for wearable optoelectronics and reduces control complexity. The proposed architecture thus helps make weak UV light visible to the naked eye. This approach also paves the way for UV-to-visible light communication²⁶⁸.

Accurate recognition of low-contrast targets in complex visual environments is essential for advanced machine vision systems. Conventional photodetectors typically suffer from weak photo-response and linear dependence of photocurrent on light intensity, limiting their ability to capture low-contrast features and rendering them susceptible to noise. Inspired by the adaptation mechanisms of the human visual system, Han *et al.* recently proposed a molybdenum disulfide (MoS_2) phototransistor with tunable sensitivity. The gate stack incorporates a hetero-diode as the photosensitive layer, comprising O_2 -plasma-treated MoS_2 and pristine MoS_2 . Fig. 6.6e²⁶⁹ and 6.6f²⁷⁰ illustrate how the retina adapts to varying illumination intensities via photoreceptors (cones and rods) and horizontal cells, enabling accurate perception even under extreme lighting conditions. In the device, the diode conductivity modulates with light intensity, dynamically redistributing the voltage across the gate dielectric and transistor channel to produce a pronounced photo-response. By adjusting the gate voltage, the photo-response range can be finely tuned, preserving high sensitivity to low-contrast targets while suppressing noise. Compared with conventional photodetectors, this device achieves a 1,000-fold enhancement in sensitivity for low-

contrast signal detection and markedly improved noise immunity. Machine vision systems built upon this device demonstrate exceptional performance in detecting low-contrast targets, underscoring its potential for next-generation vision applications. Notably, MoS₂ can be heterogeneously combined with GaN-based materials to further extend functionality.

Collectively, these advances support a central conclusion: the evolution of flexible GaN devices has shifted from isolated functional demonstrations toward system-level reconfiguration enabled by chiplet-based heterogeneous integration and monolithic multifunctional architectures. The convergence of wafer-scale membrane fabrication, advanced packaging and heterogeneous integration is dissolving the long-standing tension between mechanical compliance and functional complexity. Going forward, the seamless merging of flexible GaN-based chiplets with Si-based CMOS logic on compliant backplanes, augmented by intrinsic multi-physical coupling of mechanical, electrical and optical domains, will profoundly reshape the design paradigm for next-generation intelligent systems from soft robotics and wearable health monitors to 6G-connected edge devices. Nonetheless, key challenges must be systematically addressed before practical deployment, including long-term mechanical reliability under cyclic deformation, development of standardized design libraries for flexible GaN-based chiplets and efficient thermal management in low-thermal-mass form factors, *etc.*

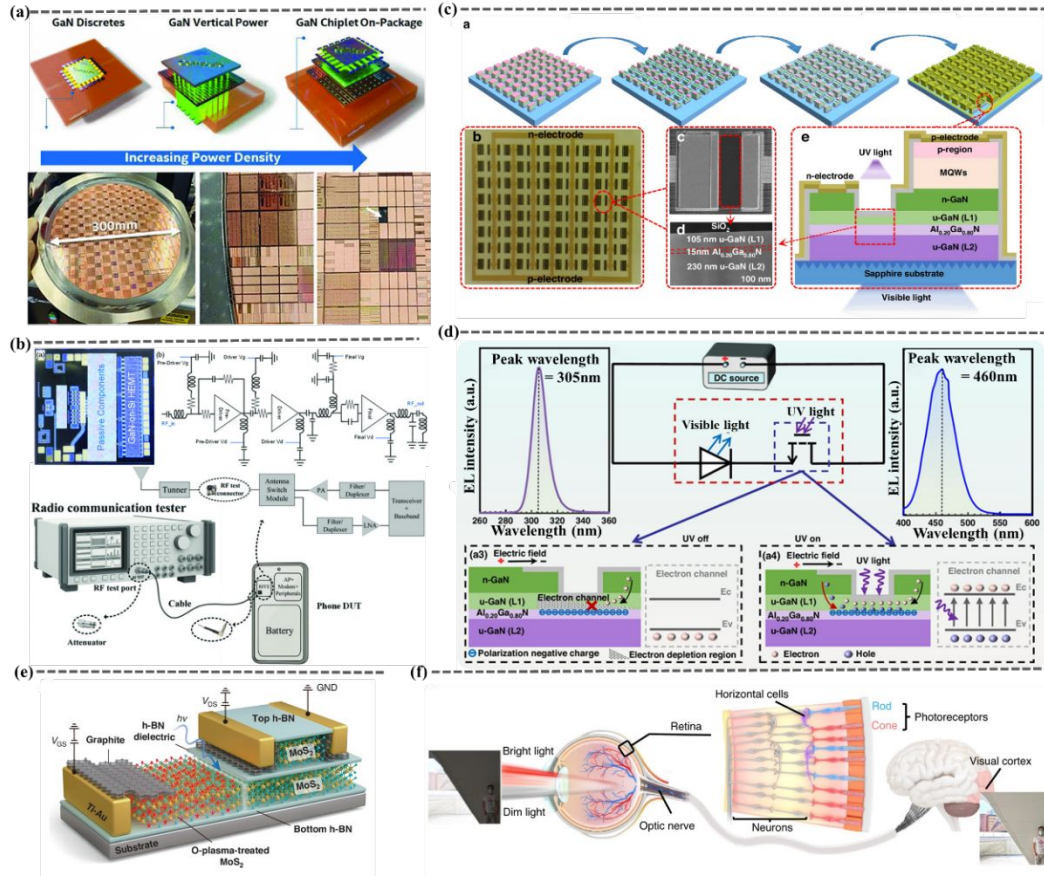


Fig. 6.6 (a) A Si substrate thickness of merely 19 μm on 300 mm GaN-on-Si wafers and an evolution chart of GaN point-of-load power solutions.²⁶⁵ Copyright © 2025, IEEE. (b) The device architecture and visual processing pipeline.²⁶⁷ Copyright © 2025, IEEE. (c) Device fabrication and structural characterization. (d) Making UV light visible by exciting polarization-gate phototransistor to achieve the energy transfer into GaN-based blue emission.²⁶⁸ Copyright © 2026, Springer Nature. (e) Schematic of the phototransistor, consisting of a MoS₂ FET integrated with a photodiode.²⁶⁹ Copyright © 2022 Springer Nature. (f) The retina adapts to different illumination intensities through photoreceptors.²⁷⁰ Copyright © 2026, Springer Nature.

7. Summary and Outlook

7.1 Summary

The field of flexible GaN-based optoelectronics has undergone a paradigm shift, evolving from thinning rigid devices into a cohesive discipline that bridges epitaxial materials science, microscale device engineering and high-throughput heterogeneous integration. This review has systematically traversed the entire lifecycle of a flexible GaN system, revealing three interdependent pillars that collectively enable mechanical adaptability without compromising the intrinsic performance advantages of III-nitride semiconductors. First, the advent of vdWE on two-dimensional materials has fundamentally redefined the growth-substrate relationship. By exploiting the weak out-of-plane interactions of graphene, h-BN and TMDs, researchers have circumvented the stringent lattice-matching constraints and thermal expansion mismatches that have long plagued GaN heteroepitaxy. This interfacial engineering not only yields single-crystalline films with defect densities approaching those of conventional rigid substrates, but also transforms the epilayer-substrate interface into a natural, non-destructive release plane. The ability to exfoliate, transfer and even recycle expensive native substrates positions vdWE as a cornerstone for sustainable, large-area flexible electronics manufacturing. Second, we have highlighted the diversification of functional device architectures tailored for flexible platforms. The transition from rigid wafer-scale processes to discrete and transferrable microscale units demonstrates that performance metrics such as external quantum efficiency, responsivity and modulation bandwidth can be largely retained or even enhanced by strain engineering. Notably, the emergence of flexible GaN neuromorphic devices signifies a critical expansion beyond conventional optoelectronics into the realm of intelligent sensing. By harnessing persistent photoconductivity and charge trapping dynamics, GaN heterostructures are now capable of emulating synaptic plasticity, thereby enabling in-sensor computing and low-power edge processing within a mechanically compliant form factor. Third, the development of mass transfer and heterogeneous integration technologies provides the

essential bridge between high-performance discrete devices and functional systems. Techniques such as LIFT, elastomeric stamp printing and FSA have matured to offer viable pathways for assembling millions of micro-scale GaN components onto flexible backplanes with high throughput and sub-micron precision. When coupled with advanced TFT backplane technologies, these integration schemes enable the construction of active-matrix displays, conformable sensor skins and closed-loop artificial vision systems. In essence, the synergy between interfacial epitaxial design and scalable assembly has transformed flexible GaN from a laboratory curiosity into a tangible platform for next-generation wearable and bio-integrated electronics. Then, the critical roles of flexible backplane electronics and heterogeneous integration strategies are addressed in constructing closed-loop systems for displays, sensing and brain-inspired computing. By highlighting the interplay between materials science, mechanical engineering and device physics, this review aims to delineate the future trajectories for high-performance mechanically adaptable GaN-based intelligent systems.

7.2 Outlook and Insights

Despite remarkable progress, current flexible GaN technology largely represents the mechanical deformation of rigid device architectures. Most demonstrations still rely on post-growth transfer onto polymer substrates, leaving fundamental challenges unresolved in thermal management, mechanical reliability and scalable manufacturing. Meanwhile, the long-term mechanical fatigue behavior under cyclic bending remains poorly understood. The yield of high-density micro-device mass transfer, although exceeding 99.9% in research settings, still suffers from statistical defects that become prohibitive when assembling millions of chiplets for commercial displays. Addressing these challenges will require concerted efforts across materials engineering, device design and manufacturing science.

In the near future (5-10 years), we anticipate the development of hybrid thermal spreading layers that can raise the effective thermal conductivity of flexible substrates without sacrificing mechanical compliance. Standardized accelerated aging protocols and in situ mechanical characterization will be essential to establish fatigue-lifetime models for flexible GaN devices. Moreover, the integration of self-aligned transfer techniques with real-time defect inspection is expected to push mass-transfer yields toward 99.999%, a threshold required for cost-competitive large-area displays. The convergence of vdWE and wafer-scale membrane fabrication will likely enable foundry-compatible processes for flexible GaN chiplets. The establishment of open design libraries will lower the barrier for system integrators to co-design GaN optoelectronics with Si CMOS on flexible backplanes. We foresee that super-flexibility will become routine, opening applications in conformal biomedical patches and soft robotics. At the device level, the combination of piezotronic effect and neuromorphic computing could yield self-powered sensory edges that preprocess tactile and optical signals locally, drastically reducing data transmission to external processors.

Looking further ahead, the coming decades will witness a transition toward imperceptible and intelligent systems, driven by several disruptive vectors. Strain-tunable quantum photonic circuits could enable mechanically reconfigurable topological waveguides and wearable quantum sensors, while bio-hybrid synapses integrating GaN nanostructures with self-healing polymers could yield damage-agnostic neural implants capable of simultaneous sensing and optogenetic stimulation. Concurrently, physics-informed machine learning and generative AI will accelerate the inverse design of morphing structures that autonomously adapt to physiological or environmental cues. According to the large-area arrays that sense, compute and communicate using ambient energy alone, unique confluence of piezoelectric, photo-responsive and synaptic properties positions GaN as an ideal platform for zero-power sentient skins. While near-term challenges in thermal management and mass transfer persist, the convergence of 2D materials, advanced

manufacturing and computational intelligence will propel flexible GaN from the laboratory toward seamless integration into a wide range of applications.

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Conflict of Interest

The authors have no conflicts to disclose.

Contributions

Y.K.Z., C.Y.X. and J.Y.Z. wrote the original draft of this work. Y.K.Z. conceived the idea. Q.S., Y.K.Z., F.Y. and X.H. guided the work. Y.K.Z., Q.S., F.Y. and J.Y.Z. carried out the funding acquisition and project administration. Y.K.Z., C.Y.X. and J.Y.Z. carried out the visualization of this work. C.Y.X., J.Y.Z. and J.K.K. performed the investigation. All authors reviewed this manuscript.

References

1. Kim, T. S. *et al.* Future trends of display technology: micro-LEDs toward transparent, free-form, and near-eye displays. *Light Sci. Appl.* **14**, 335 (2025).
2. Nagata, T. *et al.* Effects of low temperature buffer layer on all-sputtered epitaxial GaN/AlN film on Si (111) substrate. *Jpn. J. Appl. Phys.* **60**, SCCG03 (2021).
3. Li, P. *et al.* Flexible Quantum-Dot Color-Conversion Layer Based on Microfluidics for Full-Color Micro-LEDs. *Micromachines* **13**, 448 (2022).

4. Zhang, S. *et al.* Research Progress of Micro-LED Display Technology. *Crystals* **13**, 1001 (2023).
5. Kadowaki, T. *et al.* Uni-traveling-carrier photodiode based on MoS₂/GaN van der Waals heterojunction for high-speed visible-light detection. *Nat. Commun.* **16**, 10471 (2025).
6. Kim, J. *et al.* Principle of direct van der Waals epitaxy of single-crystalline films on epitaxial graphene. *Nat. Commun.* **5**, 4836 (2014).
7. Tang, C. G., Hou, K. & Leong, W. L. The Quest for Air Stability in Organic Semiconductors. *Chem. Mater.* **36**, 28–53 (2024).
8. Chen, X. *et al.* Epitaxial Lift-Off of Flexible GaN-Based HEMT Arrays with Performances Optimization by the Piezotronic Effect. *Nano-Micro Lett.* **13**, 67 (2021).
9. Guo, X., Han, L. & Hou, X. Insights into the device structure, processing and material design for an organic thin-film transistor towards functional circuit integration. *Mater. Chem. Front.* **5**, 6760–6778 (2021).
10. Luo, D. *et al.* Triggering avalanche-like ultraviolet photomultiplication phenomena in ultrathin amorphous/crystalline gallium nitride heterostructures. *Sci. Adv.* **12**, eaea7319 (2026).
11. Zhou, M. *et al.* Improving multifunctional monolithic nano-device by single (Al,Ga)N nanowire/graphene van der Waals heterostructure for neuromorphic computing, photodetection and imaging. *Commun. Mater.* **6**, 83 (2025).
12. Jiang, M. *et al.* A dual-mode transparent device for 360° quasi-omnidirectional self-driven photodetection and efficient ultralow-power neuromorphic computing. *Light Sci. Appl.* **14**, 273 (2025).
13. Hu, L. *et al.* Flexible micro-LED display and its application in Gbps multi-channel visible light communication. *Npj Flex. Electron.* **6**, 100 (2022).
14. Wang, Z. *et al.* Full-color micro-LED display based on a single chip with two types of InGaN/GaN MQWs. *Opt. Lett.* **46**, 4358–4361 (2021).
15. Jeong, J. *et al.* Heterogeneous and Monolithic 3D Integration of III–V-Based Radio

- Frequency Devices on Si CMOS Circuits. *ACS Nano* **16**, 9031–9040 (2022).
16. Jiang, M. *et al.* A dual-mode transparent device for 360° quasi-omnidirectional self-driven photodetection and efficient ultralow-power neuromorphic computing. *Light Sci. Appl.* **14**, 273 (2025).
 17. Kathe, C. *et al.* Wireless closed-loop optogenetics across the entire dorsoventral spinal cord in mice. *Nat. Biotechnol.* **40**, 198–208 (2022).
 18. Kim, H.-M. *et al.* 23-4: Full Color, Active-Matrix Micro-LED Display with Dual Gate a-IGZO TFT Backplane. *SID Symp. Dig. Tech. Pap.* **51**, 335–338 (2020).
 19. Lee, H. E. *et al.* Trichogenic Photostimulation Using Monolithic Flexible Vertical AlGaInP Light-Emitting Diodes. *ACS Nano* **12**, 9587–9595 (2018).
 20. Lee, S.-L., Cheng, C.-C., Liu, C.-J., Yeh, C.-N. & Lin, Y.-C. 9.4-inch 228-ppi flexible micro-LED display. *J. Soc. Inf. Disp.* **29**, 360–369 (2021).
 21. Lin, C.-C. *et al.* The micro-LED roadmap: status quo and prospects. *J. Phys. Photonics* **5**, 042502 (2023).
 22. Luo, Y. *et al.* A single diode with integrated photosensing, memory and processing for neuromorphic image sensors. *Nat. Electron.* 1–10 (2026) doi:10.1038/s41928-026-01588-2.
 23. Memon, M. H. *et al.* A three-terminal light emitting and detecting diode. *Nat. Electron.* **7**, 279–287 (2024).
 24. Meng, W. *et al.* Three-dimensional monolithic micro-LED display driven by atomically thin transistor matrix. *Nat. Nanotechnol.* **16**, 1231–1236 (2021).
 25. Niu, J. *et al.* Fully Flexible All-in-One Electronic Display Skin with Seamless Integration of MicroLED and Hydrogel Battery. *Adv. Funct. Mater.* **35**, 2411916 (2025).
 26. Qi, L., Li, P., Zhang, X., Wong, K. M. & Lau, K. M. Monolithic full-color active-matrix micro-LED micro-display using InGaN/AlGaInP heterogeneous integration. *Light Sci. Appl.* **12**, 258 (2023).
 27. Xu, F. *et al.* Electrically pumped single-mode microlasers with omnidirectional radiation for optical broadcasting communication. *Sci. Adv.* **12**, eaeb1682 (2026).

28. Yoon, J. *et al.* The first 200PPI stretchable micro-LED display with serpentine-shaped bridge designs. *J. Soc. Inf. Disp.* **33**, 524–532 (2025).
29. Zhou, M. *et al.* Improving multifunctional monolithic nano-device by single (Al,Ga)N nanowire/graphene van der Waals heterostructure for neuromorphic computing, photodetection and imaging. *Commun. Mater.* **6**, 83 (2025).
30. Zhou, X. *et al.* Growth, transfer printing and colour conversion techniques towards full-colour micro-LED display. *Prog. Quantum Electron.* **71**, 100263 (2020).
31. Minj, A., Cavalcoli, D. & Cavallini, A. Defect investigation in Al_{0.87}In_{0.13}N/AlN/GaN heterostructures by scanning force microscopy methods. *J. Phys. Conf. Ser.* **326**, 012011 (2011).
32. Cheng, T. S. *et al.* Effects of substrate type on the characteristics of GaN epitaxial films grown by molecular beam epitaxy. *Semicond. Sci. Technol.* **12**, 917 (1997).
33. Uren, M. J. *et al.* GaN/AlGa_xN HFETs fabricated on a SiC substrate. in *8th IEEE International Symposium on High Performance Electron Devices for Microwave and Optoelectronic Applications (Cat. No.00TH8534)* 71–75 (2000). doi:10.1109/EDMO.2000.919032.
34. Narang, K. *et al.* Investigation of carrier gas on morphological and structural characteristics of AlGa_xN/GaN HEMT. *Mater. Res. Bull.* **153**, 111875 (2022).
35. Malin, T. *et al.* Influence of substrate nitridation conditions and buffer layer structures on the crack-free GaN layers on silicon substrate grown by ammonia-assisted molecular beam epitaxy. *Thin Solid Films* **791**, 140246 (2024).
36. Ma, Y., Wu, M., Zhang, H., Sun, H. & Yuan, C. Study on thermorefectance linear relation of gallium nitride epitaxial structures at above-bandgap wavelength. *Mater. Today Phys.* **42**, 101367 (2024).
37. Yan, Z. *et al.* Atomic layer deposition technology for the development of high-quality, full-colour micro-LED displays. *Nanotechnol.* **5**, 100051 (2024).
38. Md Taib, M. I., Waheeda, S. N., Jasman, F., Yusop, M. Z. M. & Zainal, N. GaN nucleation on patterned sapphire substrate with different shapes for improved GaN

- overgrowth. *Vacuum* **197**, 110848 (2022).
39. Song, J. *et al.* Recent Advances in Nitride-Based Micro-LEDs for Next-Generation Display. *Adv. Phys. Res.* **4**, (2025).
 40. Fabunmi, T. G. *et al.* Single-crystalline GaN microdisk arrays grown on graphene for flexible micro-LED application. *Nanotechnology* **35**, 085603 (2024).
 41. Nishikawa, A., Loesing, A. & Slischka, B. 25-1: Invited Paper: Achieving high uniformity and yield of 200 mm GaN-on-Si LED epiwafers for micro LED applications with precise strain-engineering. *SID Symp. Dig. Tech. Pap.* **50**, 338–341 (2019).
 42. Chen, Z. *et al.* Terrace Engineering of the Buffer Layer: Laying the Foundation of Thick GaN Drift Layer on Si Substrates. *Adv. Electron. Mater.* **9**, (2023).
 43. Nishikawa, A., Loesing, A. & Slischka, B. 25-1: Invited Paper: Achieving high uniformity and yield of 200 mm GaN-on-Si LED epiwafers for micro LED applications with precise strain-engineering. *SID Symp. Dig. Tech. Pap.* **50**, 338–341 (2019).
 44. MacManus-Driscoll, J. L. *et al.* New approaches for achieving more perfect transition metal oxide thin films. *APL Mater.* **8**, (2020).
 45. Malin, T. *et al.* Influence of substrate nitridation conditions and buffer layer structures on the crack-free GaN layers on silicon substrate grown by ammonia-assisted molecular beam epitaxy. *Thin Solid Films* **791**, 140246 (2024).
 46. Ghosh, S. *et al.* Design of step-graded AlGaIn buffers for GaN-on-Si heterostructures grown by MOCVD. *Semicond. Sci. Technol.* **38**, 044001 (2023).
 47. Liu, Y. *et al.* Transferable GaN Films on Graphene/SiC by van der Waals Epitaxy for Flexible Devices. *Phys. Status Solidi A* **216**, 1801027 (2019).
 48. Vuong, P. *et al.* Influence of Sapphire Substrate Orientation on the van der Waals Epitaxy of III-Nitrides on 2D Hexagonal Boron Nitride: Implication for Optoelectronic Devices. *ACS Appl. Nano Mater.* **5**, 791–800 (2022).
 49. Barbier, C. *et al.* What Triggers Epitaxial Growth of GaN on Graphene? *Cryst. Growth Des.* **23**, 6517 (2023).
 50. Zhang, F. *et al.* Monolayer h-BN/C3B lateral heterostructures with promising

electronic and optical properties: A first-principles study. *Chem. Phys.* **541**, 111042 (2021).

51. Zhou, Y. *et al.* MoS₂/GaN Junction Field-Effect Transistors with Ultralow Subthreshold Swing and High On/Off Ratio via Thickness Engineering for Logic Inverters. <https://doi.org/10.1002/adfm.202410954> doi:10.1002/adfm.202410954.

52. Hwangbo, S., Hu, L., Hoang, A. T., Choi, J. Y. & Ahn, J.-H. Wafer-scale monolithic integration of full-colour micro-LED display using MoS₂ transistor. *Nat. Nanotechnol.* **17**, 500–506 (2022).

53. Liu, X. *et al.* Optoelectronic synapses with chemical-electric behaviors in gallium nitride semiconductors for biorealistic neuromorphic functionality. *Nat. Commun.* **15**, 7671 (2024).

54. Glavin, N. R. *et al.* Flexible Gallium Nitride for High-Performance, Strainable Radio-Frequency Devices. *Adv. Mater.* **29**, 1701838 (2017).

55. Tang, X. *et al.* Wafer-Scale Vertical 1D GaN Nanorods/2D MoS₂/PEDOT:PSS for Piezophototronic Effect-Enhanced Self-Powered Flexible Photodetectors. *Nano-Micro Lett.* **17**, 56 (2024).

56. Zhou, M. *et al.* Realize low-power artificial photonic synapse based on (Al,Ga)N nanowire/graphene heterojunction for neuromorphic computing. *APL Photonics* **8**, 076107 (2023).

57. Gao, Z. *et al.* Ultrathin Gallium Nitride Quantum-Disk-in-Nanowire-Enabled Reconfigurable Bioinspired Sensor for High-Accuracy Human Action Recognition. *Nano-Micro Lett.* **18**, 54 (2025).

58. Cheng, L. *et al.* Multifunctional integrated micro-light-emitting diodes for self-powered photodetection and neuromorphic computing. *Cell Rep. Phys. Sci.* **6**, 102913 (2025).

59. Feng, F. *et al.* High-power AlGa_N deep-ultraviolet micro-light-emitting diode displays for maskless photolithography. *Nat. Photonics* **19**, 101–108 (2025).

60. Sun, Y. *et al.* Room-temperature continuous-wave electrically pumped

- InGaN/GaN quantum well blue laser diode directly grown on Si. *Light Sci. Appl.* **7**, 13 (2018).
61. Kai C. *et al.* AlGaIn/GaN-Based Optoelectronic Synaptic Devices for Neuromorphic Computing. <https://doi.org/10.1002/adom.202202105>
doi:10.1002/adom.202202105.
 62. Jiang, M. *et al.* A dual-mode transparent device for 360° quasi-omnidirectional self-driven photodetection and efficient ultralow-power neuromorphic computing. *Light Sci. Appl.* **14**, 273 (2025).
 63. Zhou, M. *et al.* Realize low-power artificial photonic synapse based on (Al,Ga)N nanowire/graphene heterojunction for neuromorphic computing. *APL Photonics* **8**, 076107 (2023).
 64. Li, Q. *et al.* Single-mode GaN nanowire lasers. *Opt. Express* **20**, 17873–17879 (2012).
 65. Gao, Z. *et al.* Ultrathin Gallium Nitride Quantum-Disk-in-Nanowire-Enabled Reconfigurable Bioinspired Sensor for High-Accuracy Human Action Recognition. *Nano-Micro Lett.* **18**, 54 (2025).
 66. Mondal, R. K. *et al.* High-Performance Flexible Ultraviolet Phototransistor Based on an AlGaIn/GaN Heterojunction Membrane. *ACS Appl. Mater. Interfaces* **18**, 16700–16706 (2026).
 67. Yu, K. J., Yan, Z., Han, M. & Rogers, J. A. Inorganic semiconducting materials for flexible and stretchable electronics. *Npj Flex. Electron.* **1**, 4 (2017).
 68. Wu, H. *et al.* Ultra-high brightness Micro-LEDs with wafer-scale uniform GaN-on-silicon epilayers. *Light Sci. Appl.* **13**, 284 (2024).
 69. Park, M. *et al.* Remote epitaxy and freestanding wide bandgap semiconductor membrane technology. *Nat. Rev. Electr. Eng.* **1**, 680–689 (2024).
 70. Shin, J. *et al.* Vertical full-colour micro-LEDs via 2D materials-based layer transfer. *Nature* **614**, 81–87 (2023).
 71. Zhou, X. *et al.* Growth, transfer printing and colour conversion techniques towards

- full-colour micro-LED display. *Prog. Quantum Electron.* **71**, 100263 (2020).
72. Bandari, V. K. & Schmidt, O. G. A bright future for micro-LED displays. *Light Sci. Appl.* **13**, 317 (2024).
 73. Hsiang, E.-L., Yang, Z., Yang, Q., Lan, Y.-F. & Wu, S.-T. Prospects and challenges of mini-LED, OLED, and micro-LED displays. *J. Soc. Inf. Disp.* **29**, 446–465 (2021).
 74. Mertens, R. MicroLED Displays: Industry Status and Roadmap. *Inf. Disp.* **40**, 5–8 (2024).
 75. Ryu, J. J. *et al.* Wave energy-assisted fluidic self-assembly of LED chips for display applications. *J. Inf. Disp.* **23**, 267–272 (2022).
 76. Fan, J. *et al.* Recent Progress of Quantum Dots Light-Emitting Diodes: Materials, Device Structures, and Display Applications. *Adv. Mater.* **36**, 2312948 (2024).
 77. Monroy, E., Omnès, F. & Calle, F. Wide-bandgap semiconductor ultraviolet photodetectors. *Semicond. Sci. Technol.* **18**, R33 (2003).
 78. Zhang, R. *et al.* Recent progress in GaN-based ultraviolet photodetectors. *J. Mater. Chem. C* **13**, 10972–10996 (2025).
 79. Chen, R. *et al.* Strain-induced polarization modulation at GaN/Ti interface for flexible thin-film sensor. *Semicond. Sci. Technol.* **39**, 075022 (2024).
 80. Rogers, J. A., Someya, T. & Huang, Y. Materials and Mechanics for Stretchable Electronics. *Science* **327**, 1603–1607 (2010).
 81. Kim, D.-H., Ghaffari, R., Lu, N. & Rogers, J. A. Flexible and Stretchable Electronics for Biointegrated Devices. *Annu. Rev. Biomed. Eng.* **14**, 113–128 (2012).
 82. Yang, D. W. *et al.* Large Wavelength Response to Pressure Enabled in InGaN/GaN Microcrystal LEDs with 3D Architectures. *ACS Photonics* **7**, 1122–1128 (2020).
 83. Peng, M. *et al.* High-Resolution Dynamic Pressure Sensor Array Based on Piezo-phototronic Effect Tuned Photoluminescence Imaging. *ACS Nano* **9**, 3143–3150 (2015).
 84. Mei, Y. *et al.* A 350-nm-band GaN/AlGaIn multiple-quantum-well vertical cavity surface emitting laser. *Opt. Laser Technol.* **199**, 115076 (2026).

85. Lee, C. *et al.* Semipolar GaN-based laser diodes for Gbit/s white lighting communication: devices to systems. in 84 (2018). doi:10.1117/12.2315791.
86. Kai, C. *et al.* AlGaIn/GaN-Based Optoelectronic Synaptic Devices for Neuromorphic Computing. *Adv. Opt. Mater.* **11**, 2202105 (2023).
87. Li, X. *et al.* Optically tunable synaptic transistors based on AlGaIn/GaN heterostructure for neuromorphic vision processing. *Appl. Phys. Lett.* **127**, 213301 (2025).
88. Zhou, M. *et al.* Realize low-power artificial photonic synapse based on (Al,Ga)N nanowire/graphene heterojunction for neuromorphic computing. *APL Photonics* **8**, 076107 (2023).
89. Gu, X. *et al.* Controllable and Cost-Efficient Three-Terminal GaN Nano-Synapse for Brain-Inspired Computing. *Small* **n/a**, e14447.
90. Liu, X. *et al.* Optoelectronic synapses with chemical-electric behaviors in gallium nitride semiconductors for biorealistic neuromorphic functionality. *Nat. Commun.* **15**, 7671 (2024).
91. Yang, X. *et al.* Chemically Engineered GaN Thin Films for Light-Stimulated Artificial Synapses. *Adv. Photonics Res.* **6**, 2400146 (2025).
92. Jiang, M. *et al.* A dual-mode transparent device for 360° quasi-omnidirectional self-driven photodetection and efficient ultralow-power neuromorphic computing. *Light Sci. Appl.* **14**, 273 (2025).
93. Zhou, M. *et al.* Improving multifunctional monolithic nano-device by single (Al,Ga)N nanowire/graphene van der Waals heterostructure for neuromorphic computing, photodetection and imaging. *Commun. Mater.* **6**, 83 (2025).
94. Li, X. *et al.* Optically tunable synaptic transistors based on AlGaIn/GaN heterostructure for neuromorphic vision processing. *Appl. Phys. Lett.* **127**, (2025).
95. Gu, X. *et al.* Controllable and Cost-Efficient Three-Terminal GaN Nano-Synapse for Brain-Inspired Computing. *Small* **n/a**, e14447.
96. Liu, X. *et al.* Optoelectronic synapses with chemical-electric behaviors in gallium

nitride semiconductors for biorealistic neuromorphic functionality. *Nat. Commun.* **15**, 7671 (2024).

97. Yang X. *et al.* Chemically Engineered GaN Thin Films for Light-Stimulated Artificial Synapses. <https://doi.org/10.1002/adpr.202400146>
doi:10.1002/adpr.202400146.

98. McKee, M., Mitrovic, B., Armour, E. & Montgomery, J. Using MOCVD technology to meet key process requirements that enable micro LEDs. in *Light-Emitting Devices, Materials, and Applications XXVIII* (eds Strassburg, M., Kim, J. K. & Krames, M. R.) 58 (SPIE, San Francisco, United States, 2024). doi:10.1117/12.3008901.

99. Fabunmi, T. G. *et al.* Single-crystalline GaN microdisk arrays grown on graphene for flexible micro-LED application. *Nanotechnology* **35**, (2023).

100. Lee, S. *et al.* A discrete core-shell-like micro-light-emitting diode array grown on sapphire nano-membranes. *Sci. Rep.* **10**, 7506 (2020).

101. Jeong, J. *et al.* Remote heteroepitaxy of GaN microrod heterostructures for deformable light-emitting diodes and wafer recycle. *Sci. Adv.* **6**, eaaz5180 (2020).

102. Park, S. *et al.* Advanced Mechanical Transfer of Micro-LEDs Enabled by Structurally Modified Wide Sapphire Nanomembranes through Thermal Reflow of Photoresist. *ACS Appl. Mater. Interfaces* **16**, 42426–42434 (2024).

103. Chen, X. *et al.* Epitaxial Lift-Off of Flexible GaN-Based HEMT Arrays with Performances Optimization by the Piezotronic Effect. *Nano-Micro Lett.* **13**, 67 (2021).

104. Tian, W. *et al.* Mechanisms and Performance Analysis of GaN-Based Micro-LED Grown on Pattern Sapphire Substrate by Laser Lift-Off Process. *ECS J. Solid State Sci. Technol.* **11**, 046001 (2022).

105. Pan, Z. *et al.* The fabrication of thin-film micro-LED arrays using tape-assisted laser lift-off: towards rigid and flexible micro-displays. in *2020 International Conference on UK-China Emerging Technologies (UCET)* 1–3 (2020). doi:10.1109/UCET51115.2020.9205447.

106. Hu, L. *et al.* Flexible micro-LED display and its application in Gbps multi-

- channel visible light communication. *Npj Flex. Electron.* **6**, 100 (2022).
107. Li, J. & Liu, Z. 84-4: Transfer of Flip-Chip Structure micro-LED from Sapphire to Thin Film. *SID Symp. Dig. Tech. Pap.* **55**, 1174–1175 (2024).
 108. Ryu, J.-E. *et al.* Technological Breakthroughs in Chip Fabrication, Transfer, and Color Conversion for High-Performance Micro-LED Displays. *Adv. Mater.* **35**, 2204947 (2023).
 109. Zhang, S. *et al.* Research Progress of Micro-LED Display Technology. *Crystals* **13**, 1001 (2023).
 110. Zhao, J., Li, X., Li, Y. & Yang, L. Mass transfer strategies for MicroLED chip assembly: pick-and-place techniques and fluidic self-assembly methods. *Int. J. Smart Nano Mater.* **16**, 359–396 (2025).
 111. Wu, Y., Ma, J., Su, P., Zhang, L. & Xia, B. Full-Color Realization of Micro-LED Displays. *Nanomaterials* **10**, 2482 (2020).
 112. Cho, S., Lee, D. & Kwon, S. Fluidic Self-Assembly Transfer Technology for Micro-Led Display. in *2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII (TRANSDUCERS & EUROSENSORS XXXIII)* 402–404 (2019). doi:10.1109/TRANSDUCERS.2019.8808352.
 113. Lee, D. *et al.* Fluidic self-assembly for MicroLED displays by controlled viscosity. *Nature* **619**, 755–760 (2023).
 114. Marinov, V. R. 52-4: Laser-Enabled Extremely-High Rate Technology for μ LED Assembly. *SID Symp. Dig. Tech. Pap.* **49**, 692–695 (2018).
 115. Cui, Y., Dong, X., Ma, Z., Wang, Y. & Cao, X. Application of laser-assisted bonding in micro-LED display technology. *J. Soc. Inf. Disp.* **33**, 873–879 (2025).
 116. Wang, J. *et al.* Flexible high-resolution micro-LED display device with integrations of transparent, conductive, and highly elastic hydrogel. *Nano Res.* **16**, 11893–11899 (2023).
 117. Zhu, G., Liu, Y., Ming, R., Shi, F. & Cheng, M. Mass transfer, detection and

- repair technologies in micro-LED displays. *Sci. China Mater.* **65**, 2128–2153 (2022).
118. Song, L. *et al.* Recent progress of laser processing technology in micro-LED display manufacturing: A review. *Opt. Laser Technol.* **181**, 111710 (2025).
 119. Xie, Y. *et al.* High-yield Micro-LED laser transfer accomplished using an ablation-type release material. *APL Mater.* **12**, (2024).
 120. Haupt, O., Brune, J., Fatahilah, M. & Delmdahl, R. MicroLEDs: high precision large scale UV laser lift-off and mass transfer processes. in *Laser-based Micro- and Nanoprocessing XVI* vol. 11989 140–146 (SPIE, 2022).
 121. Ur Rehman, Z., Yang, F., Wang, M. & Zhu, T. Fundamentals and Advances in Laser-Induced Transfer. *Opt. Laser Technol.* **160**, 109065 (2023).
 122. Sun, W. *et al.* 20 μm Micro-LEDs Mass Transfer via Laser-Induced In Situ Nanoparticles Resonance Enhancement. *Small* **20**, 2309877 (2024).
 123. Song, L. *et al.* Recent progress of laser processing technology in micro-LED display manufacturing: A review. *Opt. Laser Technol.* **181**, 111710 (2025).
 124. Xia, J. *et al.* P-85: Development of High-yield Laser Lift-off Process for Micro LED Display. *SID Symp. Dig. Tech. Pap.* **51**, 1688–1690 (2020).
 125. Kim, S. *et al.* Fs pulse laser-based, micro LED chips transfer technology. in *Advances in Display Technologies XIII* vol. PC12443 PC124430B (SPIE, 2023).
 126. Tackling Mass Transfer of MicroLEDs. *Display Daily* <https://displaydaily.com/tackling-mass-transfer-of-microleds/> (2024).
 127. Zhang, B. & Haupt, O. 55.4: MicroLED - High Throughput Laser Based Mass Transfer Technology. *SID Symp. Dig. Tech. Pap.* **52**, 664–667 (2021).
 128. Lang, T. *et al.* Thin-Film Assisted Laser Transfer and Bonding (TFA-LTAB) for the Fabrication of Micro-LED Displays. *Adv. Electron. Mater.* **11**, 2400380 (2025).
 129. Li, Z., Wang, J., Ji, L., Zhang, J. & Liu, Y. A case study: dynamic behavior of a typical Micro-LED chips during laser induced forward transfer process. *Opt. Laser Technol.* **192**, 113411 (2025).
 130. Haupt, O., Brune, J., Fatahilah, M. & Delmdahl, R. MicroLEDs: high precision

large scale UV laser lift-off and mass transfer processes. in *Laser-based Micro- and Nanoprocessing XVI* vol. 11989 140–146 (SPIE, 2022).

131. Wang, Y., Cui, Y., Xia, J. & Cao, X. 91-1: Invited Paper: Micro-LED Stamp Transfer & Repair Technology for Tiling Display. *SID Symp. Dig. Tech. Pap.* **55**, 1275–1277 (2024).

132. Wang, Y. *et al.* 25.6: A Study on Micro-LED Stamp Transfer Technology: Requirement and Challenges. *SID Symp. Dig. Tech. Pap.* **52**, 347–348 (2021).

133. Pan, K. *et al.* Highly effective transfer of micro-LED pixels to the intermediate and rigid substrate with weak and tunable adhesion by thiol modification. *Nanoscale* **15**, 4420–4428 (2023).

134. Lu, H. *et al.* Optimization on Adhesive Stamp Mass-Transfer of Micro-LEDs With Support Vector Machine Model. *IEEE J. Electron Devices Soc.* **8**, 554–558 (2020).

135. Yoon, S.-U., Hwangbo, Y., Jang, B., Kim, H.-D. & Kim, J.-H. Transfer of Micro-LEDs with Roll-Based Direct Overlay Alignment for Manufacturing Transparent Displays. *Adv. Electron. Mater.* **10**, 2400236 (2024).

136. Dawson, M. D., Strain, M. J., Guilhabert, B., Jevtics, D. & Lagatsky, A. A. Planar- and roll-based transfer printing for scalable heterogeneous integration. in *Smart Photonic and Optoelectronic Integrated Circuits 2023* vol. PC12425 PC124250N (SPIE, 2023).

137. Choi, M. *et al.* Stretchable Active Matrix Inorganic Light-Emitting Diode Display Enabled by Overlay-Aligned Roll-Transfer Printing. *Adv. Funct. Mater.* **27**, 1606005 (2017).

138. Zhang, L. *et al.* Research Progress of Microtransfer Printing Technology for Flexible Electronic Integrated Manufacturing. *Micromachines* **12**, 1358 (2021).

139. Lu, H. *et al.* Optimization on Adhesive Stamp Mass-Transfer of Micro-LEDs With Support Vector Machine Model. *IEEE J. Electron Devices Soc.* **8**, 554–558 (2020).

140. Wu, Y., Ma, J., Su, P., Zhang, L. & Xia, B. Full-Color Realization of Micro-LED Displays. *Nanomaterials* **10**, 2482 (2020).

141. Li, P. *et al.* Flexible Quantum-Dot Color-Conversion Layer Based on Microfluidics for Full-Color Micro-LEDs. *Micromachines* **13**, 448 (2022).
142. Gafurov, A. N. *et al.* Registration error analysis and compensation of roll-to-roll screen printing system for flexible electronics. *Flex. Print. Electron.* **6**, 024003 (2021).
143. Jin, X., Shui, H. & Shpitalni, M. Virtual sensing and virtual metrology for spatial error monitoring of roll-to-roll manufacturing systems. *CIRP Ann.* **68**, 491–494 (2019).
144. Ji, L., Zhang, G., Zhang, J. & Liu, P. An Alternative Micro LED Mass Transfer Technology: Self-Assembly. in *2022 23rd International Conference on Electronic Packaging Technology (ICEPT)* 1–5 (2022). doi:10.1109/ICEPT56209.2022.9873296.
145. Cho, S., Lee, D. & Kwon, S. Fluidic Self-Assembly Transfer Technology for Micro-Led Display. in *2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors XXXIII (TRANSDUCERS & EUROSENSORS XXXIII)* 402–404 (2019). doi:10.1109/TRANSDUCERS.2019.8808352.
146. Bohringer, K. F., Srinivasan, U. & Howe, R. T. Modeling of capillary forces and binding sites for fluidic self-assembly. in *Technical Digest. MEMS 2001. 14th IEEE International Conference on Micro Electro Mechanical Systems (Cat. No.01CH37090)* 369–374 (2001). doi:10.1109/MEMSYS.2001.906555.
147. Do, Y. R. & Yoo, G. Y. MicroLEDs get in line. *Nat. Electron.* **6**, 182–183 (2023).
148. Park, M. *et al.* Optimizing Binding Site Spacing in Fluidic Self-Assembly for Enhanced Microchip Integration Density. *Micromachines* **15**, 300 (2024).
149. Mishra, R. K., Verma, K., Chianella, I., Goel, S. & Nezhad, H. Y. Nanomaterial integration in micro LED technology: Enhancing efficiency and applications. *Nanotechnol.* **5**, 100056 (2024).
150. Zhao, J., Li, X., Li, Y. & Yang, L. Mass transfer strategies for MicroLED chip

assembly: pick-and-place techniques and fluidic self-assembly methods. *Int. J. Smart Nano Mater.* **16**, 359–396 (2025).

151. Huang, J. *et al.* Monolithic Integration of Full-Color Microdisplay Screen with Sub-5 μm Quantum-Dot Pixels. *Adv. Mater.* **36**, 2409025 (2024).

152. Jeong, J. *et al.* 3-D On-Chip Integration of GaN Power Devices on Power Delivery Network (PDN) With Direct Heat Spreading Layer Bonding for Heterogeneous 3-D (H3D) Stacked Systems. *IEEE Trans. Electron Devices* **72**, 2654–2661 (2025).

153. Shi, J. *et al.* Advanced monolithic integration strategies on wide-bandgap semiconductors: the two-dimensional material heterogeneous integration and the system-level multi-functional integration. *Mater. Today Chem.* **49**, 103053 (2025).

154. Mishra, R. K., Verma, K., Chianella, I., Goel, S. & Nezhad, H. Y. Nanomaterial integration in micro LED technology: Enhancing efficiency and applications. *Nanotechnol.* **5**, 100056 (2024).

155. Shi, X., Wu, Z.-S. & Bao, X. Recent Advancements and Perspective of High-Performance Printed Power Sources with Multiple Form Factors. *Electrochem. Energy Rev.* **3**, 581–612 (2020).

156. Yoon, H., Jeong, S., Lee, B. & Hong, Y. A site-selective integration strategy for microdevices on conformable substrates. *Nat. Electron.* **7**, 383–395 (2024).

157. Sun, Y. *et al.* 23-3: High Transparent, Ultra-thin Flexible, Full color Mini-LED Display with IGZO TFT substrate. *SID Symp. Dig. Tech. Pap.* **51**, 332–334 (2020).

158. Powell, E. *et al.* IGZO TFT Backplane Integration for μLED Flat-Panel Display. *ECS Meet. Abstr.* **MA2024-02**, 2415 (2024).

159. Li, S. *et al.* Novel a-IGZO TFT Pixel Driving Circuit Using Hybrid PWM and PAM Method With Lower Power Consumption for Micro-LED Display. *IEEE Electron Device Lett.* **45**, 1024–1027 (2024).

160. Sheraw, C. D. *et al.* An organic thin film transistor backplane for flexible liquid crystal displays. in *58th DRC. Device Research Conference. Conference Digest (Cat.*

No.00TH8526) 107–108 (2000). doi:10.1109/DRC.2000.877109.

161. Zhu, D. *et al.* 57-2: High performance LTPS TFT Backplane Using Blue Laser Diode Annealing for Mini/Micro LED Display. *SID Symp. Dig. Tech. Pap.* **55**, 494–496 (2024).
162. Shi, X., Wu, Z.-S. & Bao, X. Recent Advancements and Perspective of High-Performance Printed Power Sources with Multiple Form Factors. *Electrochem. Energy Rev.* **3**, 581–612 (2020).
163. Im, H. *et al.* Electrical-performance and reliability improvement of flexible low-temperature polycrystalline silicon thin-film transistors via post-annealing process. *Semicond. Sci. Technol.* **37**, 105002 (2022).
164. Li, S. *et al.* Novel a-IGZO TFT Pixel Driving Circuit Using Hybrid PWM and PAM Method With Lower Power Consumption for Micro-LED Display. *IEEE Electron Device Lett.* **45**, 1024–1027 (2024).
165. Han, B. *et al.* 8.1: Invited Paper: 17-inch Flexible IGZO OLED Display by Ink-jet Printing Method. *SID Symp. Dig. Tech. Pap.* **54**, 77–80 (2023).
166. Lin, Y.-Z. *et al.* Active-Matrix Micro-LED Display Driven by Metal Oxide TFTs Using Digital PWM Method. *IEEE Trans. Electron Devices* **68**, 5656–5661 (2021).
167. Ali, A. *et al.* High quality a-InGaZnO and a-ZrAlO deposited at 375 °C by spray pyrolysis for low voltage operation TFTs. *Mater. Lett.* **367**, 136600 (2024).
168. Lee, S.-L., Cheng, C.-C., Liu, C.-J., Yeh, C.-N. & Lin, Y.-C. 9.4-inch 228-ppi flexible micro-LED display. *J. Soc. Inf. Disp.* **29**, 360–369 (2021).
169. Kim, D. *et al.* Excellent Mechanical Durability of In-Folding Stress of Poly-Si Thin-Film Transistor on Plastic Substrate Compared with Out-Folding: Generation of Gate Leakage Currents in Flexible Poly-Si Thin-Film Transistor by Out-Folding and Bias-Temperature Stress. *Adv. Eng. Mater.* **23**, 2000901 (2021).
170. Hu, S. *et al.* Exciton control enables high-performance colloidal quantum well light-emitting diodes. *Appl. Phys. Rev.* **11**, (2024).

171. Yoon, H., Jeong, S., Lee, B. & Hong, Y. A site-selective integration strategy for microdevices on conformable substrates. *Nat. Electron.* **7**, 383–395 (2024).
172. Sun, M. *et al.* Flexible Graphene Field-Effect Transistors and Their Application in Flexible Biomedical Sensing. *Nano-Micro Lett.* **17**, 34 (2024).
173. Zhang, H.-Y. *et al.* Flexible carbon fiber-based composites for electromagnetic interference shielding. *Rare Met.* **41**, 3612–3629 (2022).
174. Schaal, S. *et al.* A CMOS dynamic random access architecture for radio-frequency readout of quantum devices. *Nat. Electron.* **2**, 236–242 (2019).
175. Itoh, Y. *et al.* Electric double-layer synthesis of a spongelike, lightweight reticular membrane. *Science* **389**, 73–77 (2025).
176. Tan, X. *et al.* High Performance Sodium Ion Anodes Based on Sn4P3 Encapsulated within Amphiphilic Graphene Tubes. *Adv. Energy Mater.* **12**, 2102345 (2022).
177. Tsuda, M. *et al.* Impact of H₂-Preannealing of the Sapphire Substrate on the Crystallinity of Low-Temperature-Deposited AlN Buffer Layer. *Jpn. J. Appl. Phys.* **44**, 3913 (2005).
178. Tsuchiya, H. *et al.* 0.26-inch LED microdisplay using pixel level Cu–Cu connections of transferred GaN/Si and CMOS backplane wafer. *J. Soc. Inf. Disp.* **33**, 425–432 (2025).
179. Tsuchiya, H. *et al.* 0.26-inch LED microdisplay using pixel level Cu–Cu connections of transferred GaN/Si and CMOS backplane wafer. *J. Soc. Inf. Disp.* **33**, 425–432 (2025).
180. Tian, P., Shan, X. & Jin, Z. Micro-LED array for full-color micro-LED display and ultrafast optical communication. in *Light-Emitting Devices, Materials, and Applications XXVIII* vol. PC12906 PC129060I (SPIE, 2024).
181. Huang, W.-T. *et al.* InGaN-based blue resonant cavity micro-LEDs with staggered multiple quantum wells enabling full-color and low-crosstalk micro-LED displays. *Nanotechnol.* **5**, 100048 (2024).

182. Ma, T. *et al.* Progress in Color Conversion Technology for Micro-LED. *Adv. Mater. Technol.* **8**, 2200632 (2023).
183. Fan, X. *et al.* Recent progresses on perovskite quantum dots patterning techniques for color conversion layer in micro-LED displays. *Nanotechnol.* **5**, 100045 (2024).
184. Qi, L., Li, P., Zhang, X., Wong, K. M. & Lau, K. M. Monolithic full-color active-matrix micro-LED micro-display using InGaN/AlGaInP heterogeneous integration. *Light Sci. Appl.* **12**, 258 (2023).
185. Mun, S. *et al.* Highly Efficient Full-Color Inorganic LEDs on a Single Wafer by Using Multiple Adhesive Bonding. *Adv. Mater. Interfaces* **8**, 2100300 (2021).
186. Ryu, J.-E. *et al.* Technological Breakthroughs in Chip Fabrication, Transfer, and Color Conversion for High-Performance Micro-LED Displays. *Adv. Mater.* **35**, 2204947 (2023).
187. Yang, X. *et al.* Super retina TFT based full color microLED display via laser mass transfer. *Sci. China Inf. Sci.* **67**, 210401 (2024).
188. Zhang, S. *et al.* Research Progress of Micro-LED Display Technology. *Crystals* **13**, 1001 (2023).
189. Shim, H. C. Full-color micro-LED display with photo-patternable and highly ambient-stable perovskite quantum dot/siloxane composite as color conversion layers. *Sci. Rep.* (2023).
190. Ryu, J.-E. *et al.* Technological Breakthroughs in Chip Fabrication, Transfer, and Color Conversion for High-Performance Micro-LED Displays. *Adv. Mater.* **35**, 2204947 (2023).
191. Wu, Y., Ma, J., Su, P., Zhang, L. & Xia, B. Full-Color Realization of Micro-LED Displays. *Nanomaterials* **10**, 2482 (2020).
192. Qi, L., Li, P., Zhang, X., Wong, K. M. & Lau, K. M. Monolithic full-color active-matrix micro-LED micro-display using InGaN/AlGaInP heterogeneous integration. *Light Sci. Appl.* **12**, 258 (2023).

193. El-Ghoroury, H. S., Chuang, C.-L. & Alpaslan, Z. Y. 26.1: Invited Paper: Quantum Photonic Imager (QPI): A Novel Display Technology that Enables more than 3D Applications. *SID Symp. Dig. Tech. Pap.* **46**, 371–374 (2015).
194. Mun, S.-H. *et al.* Highly Efficient Full-Color Inorganic LEDs on a Single Wafer by Using Multiple Adhesive Bonding. *Adv. Mater. Interfaces* **8**, 2100300 (2021).
195. Huang, W.-T. *et al.* InGaN-based blue resonant cavity micro-LEDs with staggered multiple quantum wells enabling full-color and low-crosstalk micro-LED displays. *Nanotechnol.* **5**, 100048 (2024).
196. Lee, T.-Y. *et al.* Ameliorating Uniformity and Color Conversion Efficiency in Quantum Dot-Based Micro-LED Displays through Blue–UV Hybrid Structures. *Nanomaterials* **13**, 2099 (2023).
197. Chen, Z., Yan, S. & Danesh, C. MicroLED technologies and applications: characteristics, fabrication, progress, and challenges. *J. Phys. Appl. Phys.* **54**, 123001 (2021).
198. Guo, Y. *et al.* Monolithic full-color micro-LED displays featuring three-dimensional chip bonding and quantum dot-based color conversion layer. *Opt. Express* **32**, 27662–27669 (2024).
199. Gaurav, A. *et al.* Ultrahigh-resolution full-color micro-LED array with enhanced efficiency based on a color conversion technique. *Photonics Res.* **11**, 925–935 (2023).
200. Yin, Y. & Liu, Z. P-10.3: The full-color display Micro-LEDs based on quantum dots photolithography. *SID Symp. Dig. Tech. Pap.* **54**, 792–794 (2023).
201. Kang, J.-H. *et al.* RGB Arrays for Micro-Light-Emitting Diode Applications Using Nanoporous GaN Embedded with Quantum Dots. *ACS Appl. Mater. Interfaces* **12**, 30890–30895 (2020).
202. Huang, Y.-M. *et al.* High-Uniform and High-Efficient Color Conversion Nanoporous GaN-Based Micro-LED Display with Embedded Quantum Dots. *Nanomaterials* **11**, 2696 (2021).

203. El-Ghoroury, H. S., Chuang, C. & Alpaslan, Z. Y. 26.1: *Invited Paper*: Quantum Photonic Imager (QPI): A Novel Display Technology that Enables more than 3D Applications. *SID Symp. Dig. Tech. Pap.* **46**, 371–374 (2015).
204. Lin, Y., Huang, W., Zhanghu, M. & Liu, Z. Ultra-thick inkjet-printed quantum dots layer for full-color micro-LED displays. *Opt. Express* **31**, 31818–31824 (2023).
205. Zhu, L. *et al.* Microfluidic static droplet generated quantum dot arrays as color conversion layers for full-color micro-LED displays. *Nanoscale Adv.* **5**, 2743–2747 (2023).
206. Yin, Y., Lin, Y. & Liu, Z. 21-2: The full-color Micro-LEDs display based on quantum dots. *SID Symp. Dig. Tech. Pap.* **54**, 272–274 (2023).
207. Yin, Y. *et al.* 18.4: Full-Color Active-matrix Mini-LED Display based on Novel Color Conversion Technology. *SID Symp. Dig. Tech. Pap.* **52**, 244–246 (2021).
208. Jing, Y. *et al.* Photolithographic fabrication of high-resolution Micro-QLEDs towards color-conversion microdisplay. *Light Sci. Appl.* **14**, 370 (2025).
209. Li, Y. *et al.* Transfer printing quantum dots for full-color micro-LED display.
210. Kim, T.-H. *et al.* Full-colour quantum dot displays fabricated by transfer printing. *Nat. Photonics* **5**, 176–182 (2011).
211. Li, Y. *et al.* Transfer printing quantum dots for full-color micro-LED display. in *2022 19th China International Forum on Solid State Lighting & 2022 8th International Forum on Wide Bandgap Semiconductors (SSLCHINA: IFWS)* 315–317 (2023). doi:10.1109/SSLChinaIFWS57942.2023.10070974.
212. Yu, H. *et al.* A miniaturized cascaded-diode-array spectral imager. *Nat. Photonics* **19**, 1322–1329 (2025).
213. Jose, C., Areeckal, A. S., Francis, A. & Awadhiya, B. Graded barrier AlGaIn/GaN MOS-HEMT for ultra-sensitive and label-free detection of SARS-CoV-2. *Micro Nanostructures* **209**, 208379 (2026).
214. Chowdhury, S. S., Sharma, D., Kosta, A. & Roy, K. Neuromorphic computing for robotic vision: algorithms to hardware advances. *Commun. Eng.* **4**, 152 (2025).

215. Lin, C.-C. *et al.* The micro-LED roadmap: status quo and prospects. *J. Phys. Photonics* **5**, 042502 (2023).
216. Anwar, A. R. *et al.* Recent Progress in Micro-LED-Based Display Technologies. *Laser Photonics Rev.* **16**, 2100427 (2022).
217. Han, S. *et al.* AlGaInP-based Micro-LED array with enhanced optoelectrical properties. *Opt. Mater.* **114**, 110860 (2021).
218. Zhu, L. *et al.* Microfluidic static droplet generated quantum dot arrays as color conversion layers for full-color micro-LED displays. *Nanoscale Adv.* **5**, 2743–2747 (2023).
219. Yu, B., Li, Y., Li, J., Ding, X. & Li, Z. Challenges of high-yield manufacture in micro-light-emitting diodes displays: chip fabrication, mass transfer, and detection. *J. Phys. Appl. Phys.* **57**, 463001 (2024).
220. Hu, L. *et al.* Flexible micro-LED display and its application in Gbps multi-channel visible light communication. *Npj Flex. Electron.* **6**, 1–7 (2022).
221. 周律 *et al.* Micro-LED 显示及其驱动技术的研究进展. *液晶与显示* **37**, 1395–1410 (2022).
222. Song, J. *et al.* Recent Advances in Nitride-Based Micro-LEDs for Next-Generation Display. *Adv. Phys. Res.* **4**, 2400190 (2025).
223. Hoang, A. T. *et al.* Low-temperature growth of MoS₂ on polymer and thin glass substrates for flexible electronics. *Nat. Nanotechnol.* **18**, 1439–1447 (2023).
224. Yoon, J. *et al.* The first 200PPI stretchable micro-LED display with serpentine-shaped bridge designs. *J. Soc. Inf. Disp.* **33**, 524–532 (2025).
225. Kong, K. *et al.* 1-nm-thick epitaxial AlN passivation for highly efficient flexible InGaN red micro-LEDs. *Nat. Commun.* **16**, 5607 (2025).
226. Liu, C.-J. *et al.* 45-2: 14.6-inch 202-ppi Rollable Micro LED Display with Color Conversion Technology. *SID Symp. Dig. Tech. Pap.* **54**, 646–649 (2023).
227. Yuan, C., Bao, J., Zhao, J. & Chen, L. Bending mechanics simulation and device fabrication for module stacking design of flexible micro-LEDs. *J. Phys. Conf.*

Ser. **2810**, 012022 (2024).

228. Polar Light Technologies Demonstrates First Pyramidal- μ LED Micro-Display Prototype – Polar Light Technologies. <https://www.polar-light-technologies.com/polar-light-technologies-demonstrates-first-pyramidal-%c2%b5led-micro-display-prototype/> (2025).

229. Davis, S. Aledia to Showcase FlexiNova at Display Week 2025. *Semiconductor Digest* <https://www.semiconductor-digest.com/aledia-to-showcase-flexinova-at-display-week-2025/> (2025).

230. Tang, X. *et al.* Wafer-Scale Vertical 1D GaN Nanorods/2D MoS₂/PEDOT:PSS for Piezophototronic Effect-Enhanced Self-Powered Flexible Photodetectors. *Nano-Micro Lett.* **17**, 56 (2024).

231. Le Maitre, P. *et al.* Short range optical communication with GaN-on-Si microLED and microPD matrices. *J. Soc. Inf. Disp.* **32**, 797–814 (2024).

232. Jung, D. *et al.* Multilayer stretchable electronics with designs enabling a compact lateral form. *Npj Flex. Electron.* **8**, 13 (2024).

233. Yang, Z. *et al.* Direct laser transfer and thermocompression bonding process of blue GaN micro-LED arrays. *Appl. Phys. Lett.* **127**, (2025).

234. Xie, Y. *et al.* High-yield Micro-LED laser transfer accomplished using an ablation-type release material. *APL Mater.* **12**, (2024).

235. Lang, T. *et al.* Thin-Film Assisted Laser Transfer and Bonding (TFA-LTAB) for the Fabrication of Micro-LED Displays. *Adv. Electron. Mater.* **11**, 2400380 (2025).

236. Yeh, Y.-W. *et al.* Advanced Atomic Layer Deposition Technologies for Micro-LEDs and VCSELs. *Nanoscale Res. Lett.* **16**, (2021).

237. Song, W. *et al.* Recent Advances in Mechanically Transferable III-Nitride Based on 2D Buffer Strategy. *Adv. Funct. Mater.* **33**, 2209880 (2023).

238. Li, M. *et al.* A wearable and stretchable dual-wavelength LED device for home care of chronic infected wounds. *Nat. Commun.* **15**, 9380 (2024).

239. Lee, J. H. *et al.* Wearable Surface-Lighting Micro-Light-Emitting Diode Patch

- for Melanogenesis Inhibition. *Adv. Healthc. Mater.* **12**, 2201796 (2023).
240. Kim, M. S. *et al.* Clinical Validation of Face-Fit Surface-Lighting Micro Light-Emitting Diode Mask for Skin Anti-Aging Treatment. *Adv. Mater.* **36**, 2411651 (2024).
 241. Choi, J. *et al.* Implantable micro-scale LED device guided photodynamic therapy to potentiate antitumor immunity with mild visible light. *Biomater. Res.* **26**, 56 (2022).
 242. Tchernycheva, M. *et al.* Flexible optoelectronic devices based on nitride nanowires embedded in polymer films. in *2016 IEEE Nanotechnology Materials and Devices Conference (NMDC)* 1–2 (2016). doi:10.1109/NMDC.2016.7777136.
 243. Tang, X., Shen, H., Zhao, S., Li, N. & Liu, J. Flexible brain–computer interfaces. *Nat. Electron.* **6**, 109–118 (2023).
 244. Zhou, M. *et al.* Light-stimulated low-power artificial synapse based on a single GaN nanowire for neuromorphic computing. *Photonics Res.* **11**, 1667–1677 (2023).
 245. Hong, Y. J., Saroj, R. K., Park, W. I. & Yi, G.-C. One-dimensional semiconductor nanostructures grown on two-dimensional nanomaterials for flexible device applications. *APL Mater.* **9**, 060907 (2021).
 246. Reddy, J. W. *et al.* High Density, Double-Sided, Flexible Optoelectronic Neural Probes With Embedded μ LEDs. *Front. Neurosci.* **13**, (2019).
 247. Shinohara, G. *et al.* Hybrid probe combining MicroLED and neural electrode for precise neural modulation and multi-site recording. *Appl. Phys. Express* **18**, 026501 (2025).
 248. An electroencephalogram microdisplay to visualize neuronal activity on the brain surface. *Sci. Transl. Med.* <https://www.science.org/doi/10.1126/scitranslmed.adj7257>.
 249. Kai, C. *et al.* AlGaIn/GaN-Based Optoelectronic Synaptic Devices for Neuromorphic Computing. *Adv. Opt. Mater.* **11**, 2202105 (2023).
 250. Liu, D., Zhou, W. & Ma, Z. Semiconductor Nanomembrane-Based Light-

- Emitting and Photodetecting Devices. *Photonics* **3**, 40 (2016).
251. Zhang, X. *et al.* The combination of brain-computer interfaces and artificial intelligence: applications and challenges. *Ann. Transl. Med.* **8**, 712–712 (2020).
 252. Zhang, J. *et al.* Electric-stimulated controllable synaptic GaN nanodevice for neuromorphic computing. *Chip* **4**, 100149 (2025).
 253. Tesla, Inc. Tesla 2026 Q1 Earnings Call Transcript. Tesla Investor Relations, 22 Apr. 2026. <https://ir.tesla.com/press-release/tesa-2026-q1-earnings-call> (accessed 2026-06-01).
 254. TrendForce. *Humanoid Robot Market Bulletin — May 21, 2026*. TrendForce, 21 May 2026. <https://www.trendforce.com/presscenter/news/20260521-12345> (Accessed 2026-06-01).
 255. TrendForce. *Figure AI Locks Figure 04 Design for Mass Production*. TrendForce, 21 May 2026. <https://www.trendforce.com/presscenter/news/20260521-67890> (Accessed 2026-06-01).
 256. AASTOCKS. 何小鵬：面向量產版本的機器人預計三季度正式亮相 年底實現量產. AASTOCKS, 28 May 2026. <https://www.aastocks.com/Sc/Stocknews/Aaa/20260528/1234567.Htm> (Accessed 2026-06-01).
 257. [News] China Unveils First GaN Magnetic Encoder Chip for Humanoid Robot Joints. *TrendForce* <https://www.trendforce.com/news/2026/05/04/news-china-unveils-first-gan-magnetic-encoder-chip-for-humanoid-robot-joints/>.
 258. CT-Unite. *CT-21X GaN Magnetic Encoder Chip*. *TrendForce News*, 4 May 2026. <https://www.trendforce.com/news/2026/05/04/news-china-unveils-first-gan-magnetic-encoder-chip-for-humanoid-robot-joints/> (Accessed 2026-06-01).
 259. Yuan, Z., Li, Q., Lin, X., Grønli, T.-M. & Cherkaoui, S. Edge AI for Internet of Robotic Things. *IEEE Internet Things Mag.* **9**, 4–6 (2026).
 260. van Deurzen, L. *et al.* Using both faces of polar semiconductor wafers for

functional devices. *Nature* **634**, 334–340 (2024).

261. Xue, J. *et al.* Gradual mechanical deformation discernible devices based on flexible self-powered III-nitride *pin* photoelectrochemical piezo-phototronics. *Mater. Today Adv.* **26**, 100590 (2025).
262. Gao, X. *et al.* Wireless light energy harvesting and communication in a waterproof GaN optoelectronic system. *Commun. Eng.* **1**, 16 (2022).
263. Zhong, H. *et al.* Dual-Modal Sensing Platform Based on Flexible GaN Microdisk Lasers on PDMS Substrate. *Adv. Funct. Mater.* **35**, 2501566 (2025).
264. Waseem, A. *et al.* Self-powered and flexible piezo-sensors based on conductivity-controlled GaN nanowire-arrays for mimicking rapid- and slow-adapting mechanoreceptors. *Npj Flex. Electron.* **6**, 58 (2022).
265. Then, H. W. *et al.* GaN Chiplet Technology Based on 300mm GaN-on-Silicon. in *2025 IEEE International Electron Devices Meeting (IEDM)* 1–4 (IEEE, San Francisco, CA, USA, 2025). doi:10.1109/IEDM50572.2025.11353652.
266. Li, H. *et al.* GaN-on-Si HEMT for D-Band Power Amplification Demonstrating 0.67 W/mm at 10 V. *IEEE Electron Device Lett.* **46**, 1749–1752 (2025).
267. Zhang, H. *et al.* First Integration of GaN Low-Voltage PA MMIC into Mobile Handsets with Superior Efficiency Over 50%. in *2025 IEEE International Electron Devices Meeting (IEDM)* 1–4 (IEEE, San Francisco, CA, USA, 2025). doi:10.1109/IEDM50572.2025.11353809.
268. Chu, C. *et al.* Making UV light visible by exciting polarization-gate phototransistor to achieve energy transfer into GaN-based blue emission. *Light Sci. Appl.* **15**, 162 (2026).
269. Han, R. *et al.* Bioinspired phototransistor with tunable sensitivity for low-contrast target detection. *Light Sci. Appl.* **15**, 12 (2026).
270. Liao, F. *et al.* Bioinspired in-sensor visual adaptation for accurate perception. *Nat. Electron.* **5**, 84–91 (2022).