### III-Nitride Nanowires on Unconventional Substrates: from Materials to Optoelectronic Device Applications

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Review

III-nitride nanowires on unconventional substrates: From materials to optoelectronic device applications

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ABSTRACT

Group-III nitrides and their alloys feature direct bandgaps covering a broad range of the electromagnetic spectrum, making them a promising material system for various applications, such as solid state lighting, chemical/biological sensing, water splitting, medical diagnostics, and communications. In recent years, the growth of strain and defect-free group-III nitride vertical nanowires has exploded as an area of research. These nanowires, grown on various unconventional substrates, such as silicon and different metals, demonstrate potential advantages over their planar counterparts, including wavelength tunability to the near infrared and reduced efficiency droop. The low-profile and low power consumption of such nanowires also make them viable candidates for emerging applications, such as the Internet of things and artificial intelligence. Herein, we present a comprehensive review on the recent achievements made in the field of III-nitride nanowires. We compare and discuss the growth conditions and mechanisms involved in fabricating these structures via metalorganic chemical vapor deposition and molecular beam epitaxy. How the unique optical, electrical, and thermal properties of these nanowires are correlated with their growth conditions on various unconventional substrates is discussed, along with their respective applications, including light-emitting diodes, lasers, photodetectors, and photoelectrodes. Finally, we detail the remaining obstacles and challenges to fully exploit the potential of III-nitride nanowires for such practical applications.

1. Introduction

III-nitride materials are one of the most important semiconductor systems after silicon due to their versatile properties, which enable a large number of applications, such as solid-state lighting, light-emitting diode (LED) displays, dermatology, and photoelectrochemical water splitting [1–3]. Wurtzite phase III-nitrides have direct bandgaps ranging from 0.7 eV for InN to 6.0 eV for AlN, making these materials suitable as emitters from the deep ultraviolet (UV) to the near-infrared (NIR) (Fig. 1) [4,5]. Moreover, these compounds display high chemical, mechanical, and thermal stability [6,7]. Additionally, the spontaneous and piezoelectric polarization field-induced high sheet charge and saturated drift velocity associated with these materials allow their use in high-power devices...
capable of high-voltage and high-temperature operation using AlGaN/GaN high-electron-mobility transistors [8].

However, unlike GaAs or InP semiconductors, it is difficult to obtain large-size single-crystal nitride bulk substrates for the homoepitaxial growth of nitride thin films. Commercial planar III-nitrides are heteroepitaxially grown on conventional substrates, such as sapphire and silicon carbide (SiC), though the quality of the materials and the performance of the resulting devices are limited for several reasons. First, the lattice and thermal mismatch between III-nitrides and sapphire substrates results in a high-density of threading dislocations of between 10⁶ and 10⁸ cm⁻², which act as non-radiative recombination centers [9]. The existence of spontaneous and piezoelectric polarization fields in the c-plane nitrides [10], the related quantum-confined Stark effect, and the efficiency droop attributed to Auger recombination and electron leakage also contribute to the subpar properties of these heteroepitaxially grown III-nitrides [10–15]. Moreover, studies have shown that the accumulation of strain energy in conventional planar InGaN quantum well (QW) structures further reduces the luminescence efficiency of high-indium content (>25%) InGaN QWs, leading to the “green-gap” problem in LEDs fabricated from these materials [16].

In contrast, LEDs on SiC show superior performance because of their lower defect density [17]. GaN bulk substrates have also been developed in recent years to eliminate lattice mismatch and reduce polarization fields [18]. However, these advancements come with the high cost of SiC and bulk GaN substrates. GaN-on-Si is a cheaper substitution, but the lattice and thermal expansion mismatch between GaN and Si induces cracks in the nitride layers [19,20]. As a result, the development of nitride-based devices is hampered in part by the limitation of available substrates for homoepitaxial growth.

In recent years, research on planar semiconductor films has increasingly transitioned to the study of low-dimensional nanostructures, such as quantum dots (QDs), quantum rings, and nanowires (sometimes also called nanorods or nanocolumns), which have emerged as potential candidates for future electronic and optoelectronic devices [21–23]. Nanowires can be grown without catalysts using high V/III ratio growth conditions, which enhance the diffusion of III-column adatoms along the sidewalls of the nanowires, thereby promoting vertical and limiting lateral growth [24–26], a process that avoids the formation of dislocations by relieving strain laterally, thus ensuring the high-crystal quality of the materials.

Vertically aligned III-nitride nanowire devices have various advantages over their planar nitride counterparts. For instance, they can be grown on low-cost dissimilar substrates, as nanowires are less prone to dislocation and strain. III-nitride nanowires feature reduced strain due to radial relaxation, and thus also produce a smaller polarization field to increase the electron-hole wave function overlap. The III-group composition in nitride ternary structures can also be tuned in a wide range, making it possible to cover the entire visible range [27]. The light extraction properties of III-nitride nanowires are also improved due to their size and morphology [23,26]. Moreover, QDs...
In the form of disks can be embedded in the nanowire for carrier confinement.

In many cases nitride nanowires have shown the potential to overcome the abovementioned substrate-limiting obstacles in solid-state lighting [29]. For instance, Guo et al. reported white LEDs made using InGaN nanowires that showed a negligible quantum-confined Stark effect [30]. Meanwhile, Mi et al. demonstrated nearly droop-free white nanowire LEDs with an internal quantum efficiency of up to 57% [31]. And Ra et al. achieved polarization-free nanowire LEDs using high-quality non-polar and semi-polar InGaN/GaN quantum-well (QW) structures coaxially grown on n-GaN nanowires [32]. In 2014, we reported the fabrication of an InGaN/GaN quantum-disks (Qdisks)-in-nanowire LED with a peak emission of about 830 nm and a linewidth of approximately 290 nm. Furthermore, we demonstrated the transfer of these nanowire-based LEDs onto copper substrates, paving the way for the eventual realization of practical high-power LEDs [33]. Besides nanowire LEDs, III-nitride nanowire lasers emitting from green to NIR wavelengths have also been demonstrated on silicon substrates [33–36].

Fig. 2 shows the number of publications per year from an ISI Web of Science search using the keywords “nitride” and “nanowires.” Since 2000, nitride nanowire research has become increasingly popular due to the advantages of their improved light harvesting capabilities and their ability to be grown on dissimilar substrates with low strain. However, despite the high-quality materials that can be fabricated using nanowires, their large surface areas and thus the presence of a high density of surface states can create new problems [37]. For instance, the large specific surface areas of nanowire devices limits their quantum efficiency due to Shockley-Read-Hall non-radiative recombination. Additionally, researchers have reported band bending in nanowires caused by surface Fermi level pinning, which results in the separation of electron-hole pairs [38–40]. Nanowire arrays also have less active volume per unit area, thus less light-emitting media than a comparable thin film. Finally, defects along the sidewalls can be generated when coalescence occurs during growth, which degrades the crystal quality [41].

Until now, as a research community, we lack a good resource that appropriately summarizes how the unique optical, electrical, and thermal properties of these nanowires are correlated with their growth conditions on various unconventional substrates, along with their respective applications, including LEDs, lasers, photodetectors, and photoelectrodes. Therefore, a comprehensive review on the recent achievements made in the field of III-nitride nanowires is warranted. Although the top-down approach for fabricating nanowires has been shown effective, enabling high fill factors and red-yellow-green light emission in LED devices [42], this fabrication process is complex and involves defective materials on sapphire substrates [43]. In this review, we instead focus on the bottom-up approach to fabricate III-nitride nanowires and discuss the broad applications made possible by the high quality materials produced with this technique. Unlike other review papers on nitride nanowires, this review will provide an overview of III-nitride nanowires grown on different substrates such as Si, metal, quartz. Techniques for growing III-nitride nanowires, growth mechanisms, and their fundamental properties are summarized in Section 2. In Section 3, we examine III-nitride nanowires grown on various unconventional substrates, investigating their unique characteristics and corresponding applications in light-emitting diodes, lasers, photodetectors, and so on. This is followed by an elaboration on the challenges and problems within this field in Section 4. Finally, we present a summary and future perspective of III-nitride nanowires in Section 5.

2. Fabrication techniques and growth mechanisms of nitride nanowires

Semiconductor nanowires have been traditionally fabricated through catalyst-assisted methods [44]. In the vapor-liquid-solid (VLS) nucleation model, the liquid catalyst adsorbs a vapor and the nanowire grows at the liquid-solid interface, with the
catalyst droplets (e.g., Au or Ni) accelerating the chemical reaction and nitride nanowire growth [45]. While the development of catalytic methods for direction-selective growth along a particular crystallographic axis can promote a massive increase in the growth of nanowire semiconductor structures, this growth mechanism has its limitations. First, extra steps are required to prepare the catalyst droplets, and subsequent nanowire growth can only occur in a limited temperature range in which the catalyst is thermodynamically stable. Another drawback of the catalyst-assisted growth method is the potential for the incorporation of metal impurities in the nanowires, which can affect their luminescence efficiency [46]. Hence, catalyst-free growth methods have become necessary for the fabrication of group III-nitride nanowires, particularly for applications of UV devices [47].

The catalyst-free growth of nanowires has been extensively studied and reported by various groups [46,48], including our own, using methods based on GaN seed crystals to nucleate and grow nanowires [49]. In this section, we briefly summarize recent developments in catalyst-free growth techniques and mechanisms of group III-nitride nanowires, followed by discussions on the structural and optical properties of these materials (Fig. 3). We review various growth methods, including molecular beam epitaxy (MBE) [50,51], metal-organic chemical vapor deposition (MOCVD) [52,53], and hydride vapor phase epitaxy (HVPE) [29]. Due to its lack of growth-induced formation of carbon impurities [54,55] and nitrogen-vacancy related defects [56], MBE has emerged as the most favorable III-nitride nanowire catalyst-free growth method.

2.1. Molecular beam epitaxy

Invented in the 1960s by J. R. Arthur and Alfred Y. Cho at Bell Telephone Laboratories, MBE is a sophisticated physical vapor deposition method used to grow high-quality crystalline materials [57]. In the ultra-high vacuum environment of MBE, the elements in the atomic beam arrive on the substrates and react with each other to grow crystals. Since molecular nitrogen is inert, a radio-frequency plasma source is used to supply nitrogen radicals for the chemical reaction [58,59]. Group III-nitride nanowires are predominantly grown by MBE [60]. GaN nanowires grow naturally along the c-axis due to the effect of thermodynamic driving forces on the surface sticking coefficients of incoming atoms on this crystal plane [61,62]. The natural growth of c-axis GaN nanowires using MBE under various conditions, such as the relative flux of Ga and N, substrate surface orientation, and different thicknesses of the buffer layer on the surface of the substrate, has been thoroughly studied by different groups [25,63].

It is commonly reported the nitrogen-rich conditions lead to nanowire growth [64]. Moreover, the surface energy plays an important role in determining the initial radius of the GaN nanowires [65]. Bertness et al. hypothesized that the elongation of the nanowires during growth is initiated by variations in the growth rates between the crystallographic planes of GaN under nitrogen-rich conditions [36,63,66]. In other words, nitrogen-rich conditions in MBE promotes vertical growth (c-plane of GaN) and limits lateral growth. Ristić et al. proposed that gallium diffusion along the nanowire sidewalls to their peak plays a major role in the nanowire growth mechanism [25]. They illustrated a growth process in which nanowires begin to grow from GaN islands, which are formed by diffused Ga and N atoms via the Volmer-Weber growth mode (Fig. 4a). The growth from these GaN islands occurs once they reach a critical size and stability and involves (1) the incorporation of gallium atoms into the crystal through direct impingement of the molecular beam to the top surface of the nanowires, and (2) the diffusion of gallium atoms from the substrate surface toward the nanowire base to incorporate into the crystal by climbing along the lateral sidewalls (Fig. 4b) [25].

Debnath et al. described another model for catalyst-free self-organized, diffusion-driven growth of GaN nanowires on Si(111) substrates using plasma-assisted MBE [37], in which the adatoms diffuse to a nanowire’s top surface from its lateral sides because of the lower chemical potential there [57]. Debnath et al. showed their experimental results on the growth of GaN nanowires for a deposition time that exceeded the nucleation time of the nanowires. By analyzing scanning electron microscopy (SEM) images, they concluded that for thin nanowires with diameters between 10 and 80 nm, the growth process was boosted by adatom diffusion from the nanowire sidewalls. However, in thicker nanowires, adsorption of adatoms at the tip of each wire dominated the growth process, which resulted in short, thick nanowires in addition to long, thin ones with aspect ratios of up to 250. The researchers conjectured that the nanowires grew on the flat steps of the Si(111) surface via homogeneous nucleation, which involves two growth stages:

![Fig. 3. Classification of growth processes for III-nitride nanowires.](image-url)
1. **Nucleation stage.** The number of nanowires continuously increases during the nucleation stage. Debnath et al. observed that the most frequent nucleation diameter was around 10 nm, which increased with growth time.

2. **Post-nucleation stage.** The nanowire diameters as a function of length consistently increased, as demonstrated from SEM images of the nanowires at different stages of growth. This can be explained by adatom diffusion from the sides of the nanowires to the top surfaces, in addition to direct deposition at the top.

In general, continuous nucleation of nanowires was observed for relatively low nanowire densities, whereas for relatively higher nanowire densities the nucleation rate approached zero as the nanowires continued to grow rapidly in length and slowly in diameter. Debnath et al. also showed how GaN nanowire diameter distributions can vary for different growth times in the nucleation regime, with diameters increasing from 12 nm to 15 nm as the growth time was raised from 30 to 60 min. Assuming that the nucleation process was completed after 60 min, Debnath et al. hypothesized that a small number of nanowires coalesced, forming thicker structures, while many others continued to grow individually. The authors also examined the relationship between the length and diameter of the nanowires over a long growth period (360 min) [68].

Debnath et al. showed that the diffusion-induced growth process proceeds in the post-nucleation stage only if the flow of adatoms from the sidewalls to the top surface is comparable to the impinging flux rate. Based on the simplified mass transport model [67], the growth of the nanowires should be subject to the following conditions in terms of the diffusion length along the side of the nanowire (δ) and the nanowire column length (l):

1. **Re-evaporation of atoms** (δ < l). The rate of influx of adatoms from the nearby sidewalls in addition to the impinging flux at the nanowire top surface is nearly constant with the growth time. The adatoms condensed at the base of the nanowire will desorb before reaching the top.

2. **Tapering effects** (δ << l). In the case of Debnath et al., nanowires with lengths up to 3 μm exhibited no obvious tapering effects. The researchers therefore decided that for a diffusion length of around 40 nm, short diffusion lengths are not linked to the mechanism limiting nanowire growth because of the underestimation caused by the simplified assumptions in Johansson et al.’s model. [67].

In summary, MBE growth conditions are dominated by diffusion-induced growth for small diameter nanowires, while direct impingement flux dominates the growth mechanism of larger diameter nanowires [48].

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**Fig. 4.** (a) A schematic illustration of the nucleation of nanowires. (b) A schematic illustration demonstrating how nanowires grow from stable nuclei. Reproduced with permission. Ref. [25] Copyright 2008, Elsevier.
For these self-organized GaN nanowire ensembles grown randomly on substrates, there is a fairly broad statistical distribution of the structures. As a result, it is impossible to control the peak wavelength of emission, which depends on the size, position, and alloy composition of the Qdisks in the nanowires [37,69]. Selective area growth (SAG) of GaN nanowires on patterned substrates has been proposed as a way of avoiding these issues, which is accomplished by growing the nanostructures through a patterned dielectric mask deposited on the substrate. The growth conditions are adjusted to ensure selective growth on the exposed substrate only, but not on the dielectric mask. Commonly used mask layers for MBE and MOCVD nanowire SAG growth include Si$_2$N$_3$ and SiO$_2$, while Ti can also be used for MBE [70]. Growth conditions, such as temperature and nitrogen flow rate during SAG can enhance Ga diffusion and suppress parasitic nucleation on the masks [70,71]. However, while this technique is effective, patterning mask layers, using e-beam lithography and other methods, is technologically demanding in comparison to statistically random self-organized growth.

2.2. Metalorganic chemical vapor deposition and hydride vapor phase epitaxy

MOCVD is a chemical vapor deposition (CVD) technique of epitaxial growth of compound semiconductor materials that relies on the surface reaction of organic, metalorganic, and metal hydride compounds [60]. Nanowire growth using MOCVD occurs through a VLS mechanism that takes place at relatively high temperatures (800–1000 °C) at atmospheric pressure [72]. MOCVD has been widely used for LED production and demonstrates potential for commercial applications. For example, CrayoNano AS, a leader in industrial research of UV short-wavelength LEDs operating in the UV-C region, recently selected a Veeco MOCVD system for the development of nanowire-on-graphene-based devices.

Wang et al. investigated the mechanism for the growth of catalyst-free self-organized GaN nanowires on sapphire substrates by MOCVD. The authors found that the choice of carrier gas strongly influences the growth mode behavior. When nitrogen was introduced as a carrier gas during growth, gallium droplets accumulated on top of the nanowires, and they were transformed into high-quality GaN layers during the cool-down stage through the accompanying nitridation process. In contrast, when hydrogen was using as the carrier gas, a substantial improvement in the optical properties of the resulting GaN nanowires was observed, as well as an enhancement in the vertical growth rate, while no sign of gallium droplet accumulation was seen. The researchers further argued that in situ silane doping enhanced the vertical growth in both cases [73].

Invented in 1966 at RCA Laboratories, hydride vapor phase epitaxy (HVPE) is an epitaxial growth method that can be used to grow III-V compound semiconductors using carrier gases such as ammonia (NH$_3$) and hydrogen (H$_2$) [60]. HVPE is a cost-effective way of growing nitride by using low-cost source materials and reducing NH$_3$ consumption. Kim et al. demonstrated the advantages of this growth technique in their report of high-quality GaN nanorods on sapphire substrates, which were grown without the use of a catalyst or template layer [74,75]. Fig. 5a and b shows vertically aligned nanorods with homogeneous lengths and diameter grown by HVPE. Fig. 5c shows the schematic of the LED structures using these multiple quantum well (MQW) nanorods, which demonstrate high-brightness and high-efficiency blue light with enhanced internal and extraction efficiencies (Fig. 5d) [29]. HVPE can also be coupled with MOCVD growth, as demonstrated by Avit et al. who fabricated 15-μm-long c-axis InGaN/GaN MQW core/shell nanowires. The authors demonstrated that the InGaN/GaN MQW nanowires feature an abrupt interface as a result of the high aspect ratio GaN core rods grown by SAG-HVPE on a patterned nitrogen-polar AlN buffer on silicon and a InGaN/GaN shell grown by MOCVD [76].

3. III-nitride nanowires on unconventional substrates

In this section, we provide a detailed overview of recent developments in growing III-nitride nanowires on unconventional substrates, including Si, metal/foil, diamond, two-dimensional layered materials, and quartz. The structural and optical properties of...
nanowires grown using each medium will be briefly described. A broad range of their applications, including LEDs, lasers, water splitting, and communications, will also be discussed.

3.1. III-nitride nanowires on silicon

In this section, we will discuss recent progress made in nitride nanowires grown on Si and their applications, along with an overview of the fabrication process, growth mechanism, and optoelectronic devices based on such nitride nanowires, such as LEDs, lasers, solar cells, and photodetectors.

Si is one of the most commonly used substrates for microelectronics due to its abundance, low cost, commercial availability at large scale, and its capability of integration with III-V materials. Si is also the most extensively studied semiconductor and has been commercially available for several decades. If optoelectronic devices can be incorporated into a Si platform, the optoelectronic community will benefit from the readily available and well-established fabrication tools and techniques associated with this material. Owing to the lack of availability of bulk substrates, GaN is usually grown on sapphire or SiC, which is expensive and limits the size of the finished product. Si substrates, by contrast, are cost-effective, larger in diameter, and thermally and electrically conductive. However, the large lattice mismatch between Si and GaN leads to high dislocation densities and sometimes cracks in planar devices.

Fortunately, growing nanowires on Si substrates has proven less problematic, although the natural formation of SiN and light absorption from Si remains an issue. Researchers have already produced unstrained or low strain nanowires on Si substrates, which present various advantages, such as high crystal quality, enhanced light extraction, and higher doping efficiency [30]. Additionally, Si substrates would be the best of all available platforms for future high-speed computing systems, which will require the use of chip-level optical interconnects.

3.1.1. III-nitride LEDs on silicon

Although Si cannot be used as an active region in optoelectronic devices because of its indirect band gap, it can serve as a good substrate, which was first demonstrated when Nakamura et al. [77] reported a Candela-class high brightness blue LED. However, growing heterojunction semiconductors can be tricky as many parameters must be considered, such as lattice constants, thermal conductivity, strain, and piezoelectric fields [30,78–80].

The well-established microelectronics industry based on Si has triggered interest in integrating GaN optoelectronic devices on Si substrates. To fabricate such devices, we should first be aware of the growth mechanism of III-nitride materials on Si. The best-known techniques used to grow GaN planar thin films on Si include the use of buffer layers, annealing [81–83], and wafer bonding [84,85]. In 1998, Guha et al. developed the first planar GaN-based UV and violet LED on Si(111) using MBE [86]. However, the optical power of the device was too low to be reported. Some of the factors that degrade the optical power of such LEDs are defects/dislocations, piezoelectric polarization fields, and the suppression of light extraction through total internal reflection by the substrate itself [87,88].

The large surface-to-volume ratio of nanowires compared to their planar counterparts enable effective lateral strain relaxation, which significantly reduces dislocations and piezoelectric fields [30]. Some studies have even shown that nanowires grown on any foreign substrate can be almost defect-free [33,89–92]. Fabricating GaN-based devices in the nanowire form could fully realize the potential of GaN-based materials in optoelectronics to mitigate defects and dislocations. As a result of these advantages, a large number of GaN nanowire-based LEDs grown on Si substrates have been demonstrated in the literature [30]. In 2004, Kikuchi et al. reported InGaN/GaN nanocolumn multiple quantum disk LEDs grown by radio-frequency plasma-assisted-MBE on Si substrates [89]. The LEDs showed clear diode behavior with a typical turn-on voltage of 2.5–3.0 V. Three different colored

![Fig. 6. SEM and emission images of InGaN/GaN nanocolumns with different diameters. Reproduced with permission. Ref. [93] Copyright 2010, AIP Publishing.](image-url)
LEDs were fabricated with emission peak wavelengths of 530 nm, 580 nm, and 645 nm. However, the optical power of the devices was not reported.

In 2010, the same group reported the ability to control the emission color of InGaN nanowires from blue to red by increasing the nanocolumn diameter (Fig. 6). The authors hypothesized that this emission color change was induced by different compositions of indium due to the beam shadow effect and the diffusion length difference of group-III adatoms on the sidewalls for nanocolumns of different diameters [93]. The technique of achieving different emission by tuning the nanocolumn diameter presented in this work makes it possible to monolithically integrate three-primary-color LEDs for color mixing.

Guo et al. demonstrated the ability to fabricate LEDs using catalyst-free grown InGaN/GaN nanowires (areal density of $1–2 \times 10^{11} \text{cm}^{-2}$) on a Si(001) substrate by MBE [30]. Electron diffraction demonstrated that such nanowires grown with their c-plane normal to the growth direction display a wurtzite crystal structure and are almost defect-free. Additionally, the indium content of the nanowires can be changed to fabricate both green and white LEDs. Controlling the gradient of indium during epitaxy can also be used to achieve broadband emission and thus generate high-quality white light [30]. The photoluminescence and current-voltage (I–V) characteristics of the LEDs are shown in Fig. 7. The photoluminescence signal shows that the peak emission wavelength can be tuned by varying the indium content in the nanowires, whereas the inset shows that the emission peak of the nanowires does not shift as the temperature is varied between 10 K and 300 K. Large-scale production of such devices could lead to breakthroughs in solid-state lighting and in silicon photonics, because of the low-cost, high material quality, and wavelength tunability over 560 nm.

Current white lighting mainly involves in blue light source and phosphor for color conversion. Unfortunately, the phosphor has low conversion efficiency and will degrade with time. Also it will save cost without phosphor. Highly efficient phosphor-free white lighting devices are an interesting subject of study, because the emission wavelength can be tuned in a wide range, resulting in nanowires grown on Si that can be used for white lighting. In 2011, Guo et al. demonstrated an LED device using an InGaN/GaN disk structure within GaN nanowires grown on a Si substrate [94]. Utilizing this structure, the authors achieved a phosphor-free LED that could generate white light by tuning the composition of the disks. They also found that the Auger coefficient ($C_{\theta}$) of these InGaN/GaN Qdisk-based nanowires was approximately three orders of magnitude smaller than in conventional quantum wells and quantum dots, thereby eliminating the drop in efficiency as a function of injected current density. The experimentally obtained values of $C_{\theta}$ were also found to agree with theoretical results reported by Shen et al. [95].

Nguyen et al. reported the highest internal quantum efficiency of about 56.8% for a non-phosphorous white LED, which showed almost zero drop in efficiency up to the current injection density of 640 A/cm² [79]. The LEDs were based on vertically aligned InGaN dot-in-GaN wire heterostructures grown on a Si substrate by plasma-assisted MBE. A comparative study of undoped and Mg-doped dot-in-a-nanowire structures illustrated that the internal quantum efficiency for the p-doped variant was significantly higher. The color of the emission could be changed by varying the indium content in the InGaN dots and also by varying the growth conditions. The essence of this device structure is that it is possible to tune all the color components required to get white light in a single InGaN nanowire by incorporating Mg-doped InGaN dots with different indium composition. Nguyen et al. further developed InGaN/GaN/AlGaN dot-in-a-wire core/shell white LEDs on a Si substrate, in order to mitigate surface recombination and break the carrier injection efficiency bottleneck. The structure provides three-dimensional carrier confinement, leading to over 2 orders of magnitude enhancement in the output power of the LEDs while demonstrating stable white-light emission (Fig. 8) [96].

Besides visible and white LEDs, emission from III-nitride nanowires can also extend to the UV region. In 2008, Sekiguchi et al. demonstrated the first ever dislocation-free AlGaN/GaN nanocolumn-based UV LEDs on Si(111), which featured a peak emission wavelength of 354 nm [97,98]. The device showed good diode characteristics with a turn-on voltage and series resistance of approximately 4 V and 18 Ω, respectively. Three LEDs were studied, each with a different aluminum content (8.8%, 13.1%, and 25.1%), and the electroluminescence signal for each device was recorded at 50 mA of injection current, as shown in Fig. 9. The linewidth decreased from 300 meV (~60 nm) to 200 meV (~40 nm) when the aluminum content was increased from 8.8% to 25.1% [97]. This narrowing linewidth effect is the result of the suppression of electron flow reaching the p-AlGaN cladding layers used in the structure, which prevents
the deep-level emissions described in Park et al.’s study [99]. Sekiguchi et al. also demonstrated the integrated electroluminescence response of the LEDs to a pulse current with duty cycles of 0.5% and 5% and DC injection currents [97,98]. The heating effect of DC injection breaks the contact of the LEDs after the current reaches 100 mA, whereas for the pulse injection (5 μs current pulse) the current increased to over 300 mA without breaking the contact. The ratio of the integrated electroluminescence of LEDs at 100 mA for pulse injection versus DC injection was 2.8, due to the excessive heat generated during DC injection.

Carnevale et al. [100–102] reported a UV-LED using AlGaN nanowires on Si based on a strategy of improving the conductivity of the nitride by grading the composition of the AlGaN nanowires to produce a polarization charge rather than by impurity-doping with Mg. In this manner, the authors were able to resolve the doping issue in wide-band-gap semiconductors caused by the large activation energy of Mg in nitride [103]. As shown in Fig. 10a, the graded AlGaN layers that Carnevale et al. used in their device easily provides holes for LEDs, thus the Mg concentration can be reduced to achieve low reflective losses. As a result of these modifications, the device with polarization induced n-AlGaN and p-AlGaN shows rectification behavior and electroluminescence (Fig. 10b).

In 2015, Zetian Mi’s group from McGill University reported the first 210 nm emitting nitrogen polar AlN nanowire LEDs on Si with a low turn-on voltage of about 6 V [104]. Later, the same group reported a sub-milliwatt UV-LED emitting at 242 nm by implementing an n+ -GaN/p + -AlGaN tunnel junction to enhance the hole injection [105]. In 2017, the output power of a UV-C LED was further increased to 8 mW by using AlGaN core/shell nanowires [106]. Moreover, the dominant light emission direction comes from the top
surface of the nanowires, as demonstrated by angle dependent electroluminescence studies, due to the strong light scattering effect. This behavior is completely different from conventional planar UV LEDs, in which the light is transverse magnetic polarized, and thus such nanowires offer a way of realizing a surface emitting UV light source [107].

In 2017, we demonstrated a droop-free UV LED based on defect-free AlGaN Qdisks in nanowires on a Ti/silicon substrate. The 1D band modeling of the structures in nextnano software showed a significantly large overlap in the wave functions of the electrons and holes of the Qdisks, which is associated with a reduced piezoelectric field in such structures. More importantly, with regard to the electrical characterization of the device, we observed no thermal rollover up to a current density of 120 A/cm². Building on this previous work, we further utilized a pendeo-epitaxy technique for the top p-GaN layer growth to achieve a self-planarized Qdisk UV-B LED grown on silicon using dislocation-free AlGaN nanowires grown by plasma-assisted MBE that featured a fill factor of less than 95% [49,50]. The excellent crystal quality of the material during the growth and fabrication process was evident in the strong photoluminescence and electroluminescence emissions, high electron-hole wave function overlap, low piezoelectric fields, and small linewidth (20 nm) with a peak emission wavelength of 303 nm.

Different from most LEDs, which rely on the use of an alternating current (AC) to low-voltage direct current (DC) converter, Mi's...
group reported AC operated nanowire LEDs on Si through the successful monolithic integration of GaN nanowire LEDs p-doped at the top (p-GaN up) or bottom (p-GaN down) of each structure grown on the wafer by SAG [108]. The tunnel junction in these nanowire LEDs eliminates the use of p-GaN contact layers and enables reverse polarity operation, as shown in Fig. 11.

LEDs are most typically used for lighting applications. However, free-space and optical data communications utilizing the high-speed ON-OFF performance of III-nitride nanowire LEDs are also of significant importance. The high-speed performance is limited by the long electron-hole lifetimes of III-nitride materials due to spontaneous and piezoelectric polarization effects [109]. To address this issue, Koester et al. [109] developed m-planar polarization-free core/shell InGaN/GaN nanowire LEDs grown on Si (111) substrates using MOCVD. At room temperature, the authors determined via time-resolved electroluminescence spectra that the 90–10% rise-fall times of these nanowire LEDs were about 220 ps and 210 ps, respectively, under GHz electrical excitation, potentially leading to an ON-OFF key operation rate of about 1 Gbps (Fig. 12). In 2016, we also presented a white light-emitting device for optical communication, which was based on an ultra-broad linewidth orange nanowire LED accompanied by a blue laser diode with a linewidth of less than 1 nm [110, 111]. The color-rendering index and correlated color temperature of the device were reported to be 83.1 and 4138 K, respectively. The beauty of such device is it is phosphor-free and at the same time can transmit data at high speeds (1.06 Gbps) with a forward error correction compliant bit-error rate of $1.93 \times 10^{-3}$, which was obtained using the ON-OFF keying non-return-to-zero modulation scheme.

Moreover, recent advances in understanding the relative poor performance of LEDs on Si point directly to surface recombination in nanowires. The origins of surface recombination include unoccupied Ga dangling bonds and surface defects induced by the strained InGaN active region [96, 112]. Therefore, passivation of InGaN/GaN nanowire structures helps to suppress the effect of non-radiative recombination caused by the large density of surface states [113].

We demonstrated a surface passivation process using octadecylthiol (ODT, C$_{18}$H$_{38}$S), which features a thiol group (C-SH) that can bond to the surface of InGaN/GaN nanowires grown on Si(111) in order to alter the surface dynamic charge and therefore recover the band-edge emission of these materials. The resulting devices showed a fourfold increase in the photoluminescent peak intensity, and about a 50% increase in the peak external quantum efficiency (Fig. 13) [35]. Additionally, time-resolved secondary electron images of the nanowires before and after ODT passivation demonstrated that the surface recombination velocity was significantly reduced after treatment [114, 115]. The slow fading of the dark signal as a function of time in ODT passivated nanowires indicates the longer lifetime of the carriers in the excited state, which can be attributed to the significant reduction of nonradiative carrier recombination after surface passivation.

However, ODT passivation might affect the electronic properties of the nanowires. Khan et al. reported that after ODT passivation their InGaN nanowire arrays preserved their shape, but the researchers also observed an amorphous coating on the surface [116]. The presence of this coating can be interpreted as severe polymeric deposition, which may have affected the photoemission properties of the nanowires. The use of 1,2-ethanedithiol (C$_2$H$_4$(SH)$_2$), an alkanethiol with a much shorter carbon chain compared to ODT, can mitigate or prevent polymeric deposition and thus preserve the integrity of the nanowires.

Table 1 summarizes some of the developments in nanowire technology of InGaN/GaN LEDs on Si substrates. The emission of these LEDs ranges from the UV to IR. However, far less research has been done at the device level in the IR region compared to those that function in the UV and visible wavelengths. This lack of research might indicate that nitride-based nanowires are ill-suited for IR applications.

### 3.1.2. III-nitride nanowire lasers on silicon

Typical laser diodes include edge-emitting lasers (EEL) and vertical-cavity surface emitting lasers (VCSEL). Both laser types require mirror-facets and/or distributed Bragg reflectors to create resonant cavities for lasing action. EEL emits photons from mirror facets with current injection through the top and bottom electrodes. In contrast, VCSEL emits photons from the top aperture and uses two Bragg mirrors, the upper of which is designed to be less reflective than the lower.

![Fig. 12. (a) SEM micrograph of InGaN/GaN core/shell nanowires. (b) Schematic of the nanowire LED, and (c) time-resolved electroluminescence signal recorded for a pulse width of 500 ps and a frequency of 1.1 GHz. Reproduced with permission. Ref. [109] Copyright 2015, American Chemical Society.](image-url)
Currently, the growth of nitride laser diodes has been demonstrated on several different substrates, including sapphire, GaN, and Si with varying degrees of success, primarily due to the dislocation issues related to lattice and thermal mismatch between nitrides and the substrates. Nakamura et al. broke through this impasse and demonstrated the first blue laser on a sapphire substrate in 1996 by solving the p-type doping issue through activated Mg acceptors [118]. Weng et al. and Mei et al. also solved the strain problem by using a InGaN quantum dot structure on a c-plane sapphire substrate to produce a yellow-green VCSEL system [119,120].

The GaN substrate is currently the best candidate for producing an InGaN-based planar laser, owing to its low threading dislocation density of $10^4$ cm$^{-2}$. With this in mind, the Nichia and Osram Corporations fabricated their green laser diode products on c-plane GaN.
substrates \[121,122\]. Lin et al. also grew planar GaN on semi-polar GaN substrates, successfully fabricating a 516 nm green laser diode \[123\]. Finally, Farrell et al., Holder et al., and Feezell et al. have all reported GaN epitaxy on non-polar GaN substrates to achieve 404.3 nm, 405 nm, and 411.3 nm lasers, respectively \[124–126\]. Note that there is an earlier review of nanowire lasers by Mi et al. \[127\], in the present study, we review and compare recent work published in the interim, while focusing on nanowire devices grown on unconventional substrates.

Silicon substrates, when compared to sapphire and GaN substrates, are cheaper and more conductive, which has motivated studies on growing GaN materials on silicon. However, strain becomes a complicating factor as the lattice constant of silicon is very different from that of nitride materials, which can have a large impact on the electrical-to-optical conversion efficiency. Sun et al. relieved tensile strain by exploiting composition step-graded AlN/AlGaN multilayers, allowing them to achieve a silicon-based blue laser diode \[128\]. Furthermore, when pushing the emission wavelength toward the UV or "green-gap" regions, it is necessary to increase the compositional ratio of aluminum or indium in the planar quantum wells, which will lead to an increase in lattice-constant and degradation in material quality.

In recent years, many groups have adopted self-assembled nanowire structures to mitigate the challenges related to lattice strain and facilitate 2D carrier confinement. Moreover, by carefully optimizing diameter, spacing, and the fill factor of the nanowires, it is possible to obtain strong photon confinement due to the Anderson localization effect. Li et al. adopted this strategy to develop a surface emitting UV-B nanowire random laser with low threshold current density on silicon substrates \[129,130\]. Zhao et al. also demonstrated a random laser in the UV-C region using AlGaN nanowires \[105,131\]. Fig. 14a shows the schematic of each layer of an array of AlGaN nanowire lasers \[131\]. The simulation of the electric field distribution in Fig. 14b demonstrates this structure can form a high Q optical cavity. The device shows a very broad emission spectrum under low injection current, however, with increasing current, a sharp peak at 239 nm emerges due to lasing (Fig. 14c).

Frost et al. successfully fabricated an edge-emitting laser with 533 nm emission using an InGaN/GaN nanowire array on silicon. The nanowire-parylene composite cavity was formed by focused ion beam etching for polishing, followed by the deposition of a SiO2/TiO2 distributed Bragg reflector (Fig. 15a). The device showed a relatively low threshold current density of 1.76 kAcm\(^{-1}\) and 3 mW output power under 150 mA injected current \[34\], as shown in Table 2.

The red region presents a particular challenge for planar nitride materials, because operating in these frequencies requires even higher indium composition and lattice strain. Currently, this challenge has been surmounted by Jahangir et al., who used a nanowire structure on a silicon wafer to achieve a red laser with a peak wavelength of 610 nm (Fig. 15b) \[132\]. With strain-releasing and carrier-confining abilities, nitride nanowires have made further inroads into the IR region. For example, Hazari et al. fabricated an In\(_{0.85}\)Ga\(_{0.15}\)N edge-emitting laser with a lasing wavelength of 1.2 \(\mu\)m on silicon by using nanowires \[36\], as shown in Fig. 15c. This achievement would be impossible using planar quantum well structures or other material configurations due to the strain. Nanowire lasers on Si have performance comparable to or surpassing those of devices grown on GaN \[34\]. By utilizing nanowires on large-scale silicon substrates, it should be possible to achieve low-cost GaN laser diodes spanning the emission region from the UV to IR to address wide-ranging applications, such as solid-state lighting, displays, and silicon photonics.

3.1.3. III-nitride nanowire solar cells on silicon

Solar cells using III-nitride materials have been a research topic of great interest for some time. This scheme is very attractive because
Fig. 15. (a) Schematic of a green nanowire laser. The bottom shows the in-plane optical field distribution. (b) Schematic of a red nanowire laser. The bottom shows the electroluminescence spectra under injection above and below the threshold of 2.9 kA/cm². (c) L-I-V characteristics of a broad area laser (50 μm by 1 mm), the inset shows the electroluminescence spectrum above the threshold. The bottom shows the near-field image of the laser mode superimposed with the laser structure. Reproduced with permission. [Ref. 34, 36, 132] Copyright 2014, American Chemical Society. Copyright 2015, AIP Publishing. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Reported planar and nanowire-based nitride laser diodes from different research groups.

| Substrate      | Device type | Fine structure | Lasing wavelength | Threshold current density | Size (μm²) | Operating mode | Reference |
|----------------|-------------|----------------|-------------------|--------------------------|------------|----------------|-----------|
| Sapphire       | –           | MQWs           | 411.3 nm          | 3.0 kAcm⁻²               | 10 × 600   | Pulsed         | [118]     |
| Sapphire (0001)VCSEL | QDs         | 565.7 nm       | 0.83 kAcm⁻²       | –                        | –          | CW             | [120]     |
| Sapphire (0001)VCSEL | QDs         | 560.4 nm       | 0.78 kAcm⁻²       | –                        | –          | CW             | [119]     |
| c-plane GaN    | –           | MQWs           | 515 nm            | 4.4 kAcm⁻²               | 2.0 × 600  | CW             | [121]     |
| c-plane GaN    | –           | MQWs           | 520 nm            | 125 mA                   | –          | Pulsed         | [122]     |
| Semi-polar GaN| –           | Three-period MQWs | 516 nm        | 30 kAcm⁻²               | 2.0 × 1200 | CW             | [123]     |
| Non-polar GaN | –           | Five-period MQWs | 404.3 nm      | 6.8 kAcm⁻²               | 1.9 × 600  | CW             | [124]     |
| m-plane GaN    | VCSEL       | Five-period MQWs | 405 nm        | 34.48 mA                 | –          | CW             | [126]     |
| Non-polar GaN | –           | Five-period MQWs | 411.3 nm      | 3.7 kAcm⁻²               | 15 × 1000  | Pulsed         | [125]     |
| Silicon (100)  | EEL         | Three-period MQWs | 413 nm       | 4.7 kAcm⁻²               | 4.0 × 800  | CW             | [128]     |
| Silicon        | –           | Nanowires      | 239 nm           | 0.35 mA                  | –          | CW             | [131]     |
| Silicon        | –           | Nanowires      | 332.7 nm         | 12 Acm⁻²                 | 10 × 10    | CW             | [129]     |
| Silicon (100)  | EEL         | Nanowires      | 533 nm           | 1.76 Acm⁻²               | 10 × 1000  | CW             | [34]      |
| Silicon (100)  | EEL         | Nanowires      | 610 nm           | 2.9 Acm⁻²                | 1.0 × 400  | CW             | [132]     |
| Silicon (100)  | EEL         | Nanowires      | 1.2 μm           | 1.24 Acm⁻²               | 50 × 1000  | Pulsed         | [36]      |

a EEL: edge-emitting laser; VCSEL: vertical-cavity surface emitting laser; MQWs: multiple quantum wells; QDs: quantum dots; CW: continuous wave.

Fig. 16. (a) Schematic illustration of GaN nanorods on n-Si, with PMMA as filling material for the gap between nanowires, and Ni/Au as a transparent top contact of the cell. (b) Current density vs. voltage plot of the nanorod solar cell performance under different illumination intensities. (c) FF and power-conversion efficiency (n) of the cell as a function of light intensity. Reproduced with permission. Ref. [133] Copyright 2008, American Chemical Society.
the bandgap of the material can be tuned to cover the majority of the solar spectrum by adjusting the composition of the InGaN. Growing nanowires, nanorods, and nanocolumns on Si substrates is comparatively cheap, and can produce a large-size product, motivating the study of established Si-based fabrication techniques applied to nanowire-on-Si technology. However, it is crucial to optimize the growth, substrates, nanowire size/density, materials, dopant concentration, device thickness, and electrodes, as well as other factors to achieve high-efficiency.

In 2008, Tang et al. illustrated the growth of a uniform array of magnesium-doped GaN nanorods with vertical alignment on an n-type Si(111) substrate using CVD with gold nanoparticles as a catalyst [133]. Single-crystalline nanorods grown in this fashion are directed along the (0001) plane with good antireflection behavior for visible light. The p-GaN nanorods on n-Si were found to be robust, with a rectification ratio greater than $10^6$ at $\pm 0.5$ V. Under one-sun illumination (AM 1.5G), a maximum power conversion efficiency of $\sim 2.73\%$, high open-circuit voltage of $\sim 0.95$ V, a short-circuit current density of $\sim 7.6$ mA/cm$^2$, and a fill factor (FF) of $\sim 0.38$ was obtained (Fig. 16).

InN is considered a strong candidate for high-efficiency photovoltaics due to its high absorption coefficient, large drift velocity, and high carrier mobility. The implementation of InN nanowires ensures high crystalline quality and enhanced absorption. In 2011, Nguyen et al. performed a thorough morphological and optical characterization of high-quality MBE-grown intrinsic p-InN and n-InN nanowires on Si(111) [134]. This project represented the first ever InN nanowire homojunction solar cell consisting of InN:Si/i-InN/InN:Mg on n-type Si(111) substrates, producing an energy-conversion efficiency of $\sim 0.68\%$ under one-sun illumination, breaking several distinct barriers (such as p-type doping) to the development of InN-based nanoelectronics and nanophotonics. However, there is still room for improvement due to the existence of a naturally formed amorphous SiNx layer and the limited density of the nanowires due to the growth conditions. Despite these shortcomings, this work constitutes important progress for InGaN-based solar cells.

In 2012, Sarwar et al. [135] performed a simulation of InGaN/GaN nanowire solar cells on silicon using nextnano$^3$ to see if they could manipulate the strain, piezoelectric field, and effective energy barrier height of the holes for better solar cell performance. In InGaN, a higher proportion of indium is expected to result in good electrical conduction, however, it may also lead to dislocations and fractures in the epitaxial layers. To avoid such defects without degrading the overall device performance, the authors showed that graded heterojunctions can be incorporated, which produce only one-sixth the strain compared to abrupt heterojunctions and also boost the electrical injection efficiency, reducing the effective barrier height of the holes. In this manner, a maximum overall efficiency of 21% was achieved. In 2015, Mehmet et al. grew PiN solar cells using InGaN(0001) nanorods on n-Si(111) [136]. The devices showed a short-circuit current density ($J_{SC}$) of 4.6 mA/cm$^2$ and an open circuit voltage ($V_{OC}$) of 0.22 V under one-sun illumination. The distinct high current density in the devices can be attributed to the configuration of the PiN/InGaN solar cells, which feature a unique transparent layer fabricated by small angle deposition (SAD) and glancing angle deposition (GLAD) methods (Fig. 17).

Of all the work mentioned in this section, the most progress has been made in growing III-nitride solar cells on Si substrates. Although the growth of high-quality nanowires on Si substrates has already been demonstrated, there is room for improvement in terms of power conversion efficiency and the cost-effectiveness of III-nitride-based solar cells.

3.1.4 III-nitride photodetectors on Si

III-nitride is one of the most promising materials for the development of photodetectors (PDs) that cover not only the solar spectrum but also the solar-blind region between 230 and 290 nm. The development of this technology has come a long way, but has not yet reached fruition in terms of function and commercialization. Among the factors that require further study include cost-effectiveness, the size of the substrates for mass production of PDs, the practicality of such devices for high-speed communication, and their use in future optoelectronics. Single nanowire PDs have also attracted attention in III-nitride research—not just for the sake of novelty, but also because of their potential in making smaller, faster, and more efficient devices.

In 2005, Calarco et al. studied the photocurrent in GaN nanocolumns and found a consistent size-dependent effect. This strange effect was explained by size-dependent recombination barriers within the nanowires (Fig. 18) [137]. It is known that Fermi level pinning at the nanowire sidewalls induces internal electric fields in the structures [138]. Calarco et al. claimed that the interplay between the diameter of the columns and space charge extension leads to size-dependent recombination barriers within the nanowires and

![Fig. 17.](image-url) (a) Ni/Pt metal contact layer deposition on PiN/InGaN nanorods using SAD-GLAD, with top and side views. (b) J-V characteristics under dark and one-sun illumination conditions. Reproduced with permission. Ref. [136] Copyright 2015, The Japan Society of Applied Physics.
subsequently produces the observed size-dependent photoconductivity effect. For large nanowires, the spatial separation of electrons and holes reduces the surface recombination rate, as a result the photocurrent remains relatively high (Fig. 18).

Chen et al. studied the intrinsic photoconduction efficiencies in GaN nanowires grown using several different methods [139]. The authors compared both MBE and CVD grown GaN nanowires to compare the photoconduction efficiencies using normalized gain ($\Gamma_n$) and found the efficiency in CVD-grown GaN nanowires superior by almost two orders of magnitude. The researchers further looked at the temperature-dependent time-resolved photocurrent results and found the higher photoconduction efficiency in the CVD-grown nanowires was due to the higher barrier height $\phi_B$ ($160 \pm 20$ mV) of the electrons compared to MBE-grown nanowires ($20 \pm 2$ mV) due to surface band bending. However, the diameter of the nanowires grown using CVD (60 nm) and MBE (110 nm) also differed, which might be the reason for the different barrier heights. The lower surface state density in the non-polar (c-axis) MBE-grown nanowires compared to that of the polar (m-axis) CVD-grown nanowires is inferred to be one reason for the dramatic difference in $\phi_B$.

Besides these c-axis GaN nanowires, in 2014 Wang et al. successfully grew nonpolar a-axis GaN nanowires on patterned Si to make metal-semiconductor-metal (MSM) back-to-back Schottky contact PDs for high-performance UV detection [140]. The device featured ultrafast rise and decay times of less than 26 ms under excitation by 325 nm light, which the authors claimed was the best performing UV detector ever based on bare nanowires without any surface or composition modification where the surface defects are modulated by the compositions [141]. Additionally, the PD showed high spectral responsivity ($R$) and external quantum efficiency in the windows of $5.50 \times 10^3$ A/W and $8.00 \times 10^4$, respectively. More importantly, optical logic AND/OR gates were illustrated by connecting the PDs in parallel and series. PDs fabricated in this way thus have potential for applications beyond mere light detection, including stable optical logic, optical communication, and memory storage (Fig. 19).

There has been great improvement in nanowire growth and performance for PD applications. Though several major challenges have been addressed, much room for improvement remains, especially in the frequency response for optical logic devices and communication-related applications.

3.1.5. III-nitride artificial photosynthesis on Si substrates

Because of the chemical stability, large surface area, and tunable bandgap energy of InGaN nanowires (which cover nearly the entire solar spectrum), III-nitride nanowires have been applied as photoelectrodes for artificial photosynthesis, including solar water splitting and CO$_2$ reduction.

Photoelectrochemical (PEC) water splitting using III-nitride photoactive materials can be a means to enhance solar hydrogen production [92]. Typically, these III-nitride nanowires are grown on single crystalline substrates, such as sapphire or Si. However, both substrates suffer from poor interfacial charge carrier kinetics, which can be attributed to the low conductivity of sapphire or the formation of amorphous SiN$_x$ dielectric interfacial films that limit the solar-to-hydrogen (STH) conversion efficiency of the resultant III-nitride photoelectrolysis devices. For example, GaN/InGaN core/shell nanowire photoanodes were fabricated on c-plane sapphire
using MOCVD [142, 143]. Although these materials were photoactive in the deep visible range with an incident-photon-to-current conversion efficiency (IPCE) of up to 16%, the STH was very small due to the low electrical conductivity of the sapphire substrate, which resists the transport of the photogenerated charge carriers.

That being said, high-density vertically aligned InGaN-based nanowire photoelectrodes have been grown by plasma-assisted MBE on Si substrates [144–146]. Double-band InGaN/GaN core/shell nanowires grown on Si were also used for stable hydrogen production, with an IPCE of up to ~27% measured under UV and visible light irradiation [147]. Furthermore, researchers have fabricated a dual-photoelectrode device using an InGaN nanowire photocathode and a GaN nanowire photoanode (Fig. 20a), which demonstrated an open circuit potential of 1.3 V and around 20-times greater power conversion efficiency under illumination from 400 to 600 nm than individual photoelectrodes composed of InGaN nanowires in 1 mol/L HBr [144]. Moreover, by incorporating the tunnel junction,
p-InGaN nanowires were grown on low-resistivity n-Si substrates (Fig. 20b). To enhance their PEC performance, p-InGaN/n-GaN nanowires were monolithically integrated on a Si solar cell wafer [145]. The integrated photocathode achieved an enhanced bias photon-to-current conversion efficiency of approximately 8.7% at 0.33 V vs. RHE and high hydrogen generation Faradaic efficiency in the range of 97–105%. Although the InGaN-based photoelectrolysis system fabricated on Si-substrates showed a satisfactory PEC water splitting performance, their STH efficiency, which is the benchmark for solar hydrogen generation, was extremely limited. This was attributed to the formation of dielectric SiNx interfacial films between the GaN and Si-substrate, which adds additional charge carrier transport resistance, as well as a large conduction band offset, which can significantly degrade the overall photoelectrolysis device performance [148].

The use of surface passivation can improve the PEC performance of nanowire arrays on Si. For example, p-GaN nanowires passivated with 1,2-ethanedithiol resulted in a high photocurrent density of −31 mA/cm² at −0.2 V vs. RHE with an IPCE of up to 18.3% and a high stability of more than 55 h [146]. The improved charge carrier separation and the enhanced carrier lifetime after passivation played an important role in achieving high efficiency.

Besides water splitting, Mi et al. demonstrated that GaN nanowires grown on Si(111) also have application in the reduction of CO₂ into CH₄ and CO. Photoconversion to CH₄ can be enhanced with a Rh/Cr₂O₃ co-catalyst on the sidewall of the nanowires for a photoconversion rate as high as ~14.8 μmol g⁻¹ h⁻¹ [149]. Later, the same group also integrated GaN nanowires with a standard Si solar cell, which allows the absorption of a large part of the solar spectrum and selective CH₄ production over CO generation [150]. The same group further demonstrated the photoreduction of CO₂ into methanol using InGaN nanowires and irradiation by sunlight (Fig. 21). The photocatalytic activity for CO₂ reduction can also be enhanced by incorporating Mg into InGaN nanowires [151]. These studies demonstrate that nitride nanowires on Si show great potential as a photocatalyst for CO₂ reduction.

### 3.2. III-nitride Nanowires grown on metal

Despite the great success of high-quality nanowires and devices grown on low-cost, large-area Si substrates, there are a number of unresolved issues, the foremost being the significant visible light absorption by Si, which reduces quantum efficiencies and the output power of LEDs. Another issue is the natural formation of an amorphous SiNx layer when the silicon surface is exposed to a nitrogen-rich environment. This layer impedes carrier flow and heat dissipation [152].

Furthermore, because of the small diameter and lateral discontinuity of nanowires, the injected current density and the associated junction temperature in nanowire LEDs and lasers is higher than in conventional planar devices [127]. Additionally, the carriers and acoustic phonons that carry heat away transport one-dimensionally along the nanowire [153,154], leading to severe junction heating and degradation of the performance and lifetime of nanowire devices, which is only made worse when an insulating SiNx layer is found on the substrate surface [155,156]. Effective thermal management of nanowire devices is thus critical, especially in high power solid-state lighting applications [157]. For this reason, phosphor-free InGaN/GaN nanowire white LEDs and NIR LEDs have been transferred to copper substrates, and have demonstrated better light-output intensity and I–V characteristics than those of nanowire LEDs on Si [158,159]. However, this method requires complicated wafer bonding or lift-off processes. Instead, it is preferable to grow nanowires directly on electrically and thermally conductive substrates.

Although GaN nano- and microstructures have been grown on diamond and amorphous glass substrates [160,161], these techniques do not simultaneously address the absorption, thermal, and electrical conductivity issues of high-performance devices. Bulk transition metal alloys and their alloys have been used as commercial heat sinks and thermal-matching substrates for planar LEDs fabricated by complicated processes such as wafer bonding or laser lift-off [162-164]. To fix these issues, Wolz et al. demonstrated the direct growth of GaN nanowires on Ti-coated sapphire substrates [165]. They further showed that Ti was converted to TiN upon exposure of the surface to the nitrogen plasma and that GaN nanowires could be grown epitaxially on the TiN film using MBE. Later, Sarwar et al. reported the growth of nanowires on Ti- or Mo-coated Si substrates. They further demonstrated the successful fabrication of p-down GaN nanowire LEDs on Mo due to good ohmic contact with the p-type nanowires [166]. Our group also reported a UV nanowire LED grown on a Ti-coated Si substrate, which improved heat dissipation and current injection [50].

For practical design and facile fabrication of scalable, low-cost, high-power nanowire devices, it is necessary to have direct growth of high-density (~10¹⁰ cm⁻²) vertical hexagonally-shaped nanowires of high structural and optical quality on bulk-metal substrates for effective heat dissipation. In our own work, we demonstrated for the first time the direct growth of high-quality, high-density InGaN/ GaN Qdisks-in-nanowires for high-power LEDs on commercial polycrystalline Mo substrates (Fig. 22a) [5,167]. Our results confirmed

![Fig. 21. (a) Schematic of a p-InGaN/GaN nanowire photocatalyst with Pt catalyst decorating the sidewalls. (b) Methanol evolution as a function of time using Pt-decorated p-InGaN/GaN nanowires. Reproduced with permission. Ref. [151] Copyright 2016, American Chemical Society.](image-url)
The nitrogen-polar nanowires grew epitaxially on the metallic TiN transition layer \[168,169\], which also formed an ohmic contact with n-GaN \[165,170\], a good reflector for long wavelengths due to the high reflectivity of TiN \[171,172\], thereby significantly simplifying the subsequent fabrication process for high-power LEDs compared to conventional processes relying on laser-liftoff and wafer bonding.

The fabricated LEDs exhibited an ultralow turn-on voltage of \(~2\) V (Fig. 22b), and demonstrated droop-free efficiency at an unprecedentedly high-input power density of \(45\) kW/cm\(^2\), escaping the “valley of droop” for energy-efficient lighting \[5,173\].

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**Fig. 22.** (a) Schematic of nanowires grown on a Ti/Mo substrate. (b) I-V characteristics of the LED. The inset displays an optical microscope image of the device. (c) Band alignment of n-GaN on Mo. (d) Light output power and wall-plug efficiency of LEDs during a burn-in test. Reproduced with permission. Ref. \[5,167\] Copyright 2016, American Chemical Society.

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**Fig. 23.** (a) Photo of the Ti foil after nanowire growth. (b) Scanning electron micrograph of GaN nanowires grown on Ti foil. Reproduced with permission. Ref. \[180\] Copyright 2016, AIP Publishing.
nanowires on diamond (Table 3), a process which was inspired by growing nitride nanowires on silicon. In recent years, substantial progress has been made in growing nitride nanowires on metal foils would avoid the complications of conventional transfer methods, which could significantly increase throughput. Based on the previous results of GaN nanowires grown on Ti/sapphire substrates, Geelhaar et al. demonstrated the growth of vertically aligned GaN nanowires on a Ti foil, and demonstrated that the luminescence of the nanowire epilayer did not degrade upon bending to a small curvature radius of 4 mm (Fig. 23) [180]. May et al. similarly reported AlGaN nanowire UV-LEDs grown directly on flexible Ta foils [176].

Besides optoelectronic devices, nitrides on bulk metal substrates have also been utilized for water splitting to enhance charge extraction and collection. The relatively low STH efficiency of In_{x}Ga_{1-x}N-based photoelectrodes is mainly attributed to the low conductivity of conventional sapphire and Si substrates, which slow down the charge carrier transport. With bulk metal substrates, the photogenerated electrons can migrate to the counter-electrode to reduce the hydrogen ions with minimal carrier loss. Using this design, Ebaid et al. reportedly achieved 3.5% STH efficiency for pure water splitting under one-sun illumination [181].

### 3.3. III-nitride Nanowires on diamond

Due to its high thermal conductivity, sound velocity, and efficient p-type doping [182,183], diamond is an attractive substrate for fabricating high-electron-mobility transistors and UV-LEDs. In recent years, substantial progress has been made in growing nitride nanowires on diamond (Table 3), a process which was inspired by growing nitride nanowires on silicon.

In 2012, self-assembled GaN nanowires epitaxially grown on diamond were demonstrated for the first time using MBE by Schuster and colleagues, as shown in Fig. 24a [184]. The results demonstrated smaller tilt variation compared to similar nanowires grown on Si due to the absence of a SiNx layer. The authors also found the nature of the substrate only has a limited impact on the nanowire growth; the only requirement is the large lattice mismatch to ensure Volmer-Weber nucleation. In contrast, the surface orientation of a crystalline substrate defines the growth direction and the in-plane epitaxial relationship with respect to the nanowires [185]. The same group later implemented SAG of GaN nanowires on a diamond substrate in 2015, achieving optimum results using a patterned TiN mask at 890 °C (Fig. 24b) [160]. Furthermore, it was shown that the period of the hole pattern in Fig. 24b can lead to a transition from nanowire to nanotube growth. By comparison, the temperature window for self-assembled growth is much narrower than for selective-area nanowire growth on diamond substrate. Hetzl et al. obtained a growth regimes diagram based on substrate temperature and III/V flux ratio by studying the SEM results after growth [182]. The result revealed that both axial and radial growth rates are nitrogen-limited.

To study the growth mechanism, detailed cross-sectional TEM imaging of the interface between GaN nanowires and diamond substrates has been performed, which demonstrated the absence of any intermediate layer between the two materials. Thus, c-plane GaN nanowires have been grown epitaxially on diamond (111) substrates [184,185]. In addition, although mixed polarity occurs for GaN nanowires grown on diamond, it is possible to control the polarity by changing the surface chemistry and the substrate temperature, which is attributed to the interfacial bonds between the nanowires and the atomic species at the surface of the diamond [160,186]. It was found that O termination leads to an N-polar nanowire, whereas N-terminated diamond results in Ga polarity [186].

Looking for practical applications of this technology, Hetzl et al. studied GaN nanowire doping on diamond substrates and found that incorporating dopant atoms into GaN nanowires is much more efficient than for GaN thin films [187]. I-V characteristic from conductive atomic force microscopy (c-AFM) also demonstrated good rectifying behavior of GaN nanowires on diamond (Fig. 25a). This result spurred further study of the optoelectronic properties of n-type GaN on p-type diamond substrates, finding that a diode structure with low doping produced good electrical transport properties due to its high crystal and interface quality, as shown in the I-V characteristic in Fig. 25b [182,188]. The researchers also fabricated a nanowire LED that showed an emission peak at around 2.35 eV from the diamond substrate, and a second one at about 3.37 eV due to the GaN nanowires (Fig. 25c) [182,188]. The inhomogeneous distribution in the thermographic image of the LED is due to growth non-uniformity, indicating that not all nanowires in the array contribute to the device performance (Fig. 25d).

### Table 3

| Emission Wavelength | Active region material(s) | Device structure | Growth technique | Year | Reference |
|---------------------|---------------------------|------------------|------------------|------|-----------|
| 357 nm              | GaN                       | –                | MBE              | 2012 | [132]     |
| –                   | GaN                       | –                | MBE              | 2015 | [116]     |
| 357 nm              | n-GaN & p-GaN             | –                | MBE              | 2015 | [133]     |
| 368 nm              | n-GaN                     | p-diamond/n-GaN LED | MBE              | 2015 | [134]     |
| –                   | GaN                       | –                | MBE              | 2017 | [135]     |
3.4. III-nitride Nanowires on layered materials

For nitride optoelectronic devices and sensors, it is essential to grow GaN nanowires on highly conductive substrates. Compared with the substrates mentioned previously, graphite exhibits excellent performance in terms of both electrical and thermal conductivity, displays excellent stability at high temperatures, a smaller lattice mismatch with wurtzite GaN due to the hexagonal arrangement of the...
carbon atoms, and a low thermal expansion coefficient. Moreover, because of the weak atomic bonding between the layered structure of graphite and the underlying substrate, GaN thus grown can be easily transferred to other substrates, such as polymers, after growth.

In 2013, well-crystallized c-plane GaN nanorods on graphite were reported using CVD without a catalyst [189]. The minimizing of the total surface free energy and electrostatic surface energy in the wurtzite-type hexagonal structure of GaN induces the appearance of periodic repeats of Ga-terminated and N-terminated facets, leading to the corrugated morphology of the nanorods. In 2014, GaN microrods and coaxial In$_x$Ga$_{1-x}$/N/GaN MQW heterostructures were grown on graphene films on SiO$_2$/Si substrates by MOCVD (Fig. 26). The CVD-grown graphene was transferred to the SiO$_2$/Si substrates, and a GaN buffer layer can be grown to improve the vertical alignment of the micro-rods. The resultant LEDs were further transferred to a polymer substrate to form flexible LEDs, which proved highly reliable, with no significant degradation in performance after many bending cycles [190]. The dominant electroluminescent emission was observed at 437 nm at an injection current of 2.6 mA, with a blue shift to 407 nm observed at an injection current of 10 mA.

Graphene films on other substrates have also been used to grow GaN nanorods and nanowires. In 2015, Heilmann et al. reported n-GaN nanorods on a graphene/sapphire substrate using MOCVD [191,196]. It was found that these nanorods grew predominantly on defective regions of graphene, which also served as a back contact for the GaN nanorods. I–V measurements were carried out on a single GaN nanorod using a nanoprober, which proves the viability of graphene as a conductive electrode. Later, the researchers reported GaN nanorods on graphene/silicon [194]. n-GaN nanorods on graphene/Si(111) have been used as efficient UV photoconductive devices [192,193]. The high-quality n-GaN nanorods grown on graphene exhibit extremely low carrier trap density in the photoconductive

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**Fig. 26.** (a) The GaN micro-rod growth process featuring a GaN buffer layer on a CVD grown graphene substrate on SiO$_2$/Si. (b) The fabrication process for flexible micro-rod LEDs. (c) Optical images of the LED. (d) The injection-dependent electroluminescence spectra of the fabricated LEDs. Reproduced with permission. Ref. [190] Copyright 2014, AIP Publishing.
channel, leading to ten-fold enhancement in photocurrent along with increased photoresponsivity and sensitivity. To increase the nucleation density of nanowires, Heilmann et al. further used nanometer-sized AlGaN as nucleation islands [194].

In 2016, GaN nanorods with emission at 357 nm on graphene were grown using MBE [195], which is highly selective to graphene flakes to avoid growth on the bare substrate. The researchers also observed the epitaxial relationship between the wurtzite GaN and the carbon zigzag chains. Later, Fernández-Garrido et al. reported the direct growth of GaN nanowires on multilayer graphene synthesized on SiC using MBE, which nucleated preferentially at step edges and morphological defects [197].

Besides graphene and graphite, large-area MoS₂ layers have also been used for nitride nanowire growth (see Table 4). In 2017, for the first time, InGaN/GaN nanowires on MoS₂ were realized via quasi-van der Waals epitaxy (vdWE) using MBE [198]. The L–I–V curves of the resultant LEDs displayed a turn-on voltage of ~2 V (Fig. 27a). Different emission wavelengths were obtained (470 nm and 635 nm) by changing the growth condition of the Qdisks incorporated in the nanowires (Fig. 27b). The authors also showed that the MoS₂ layer could serve as both a buffer layer for high-quality GaN epitaxy and a sacrificial layer for device lift-off (Fig. 27c).

3.5. III-nitride Nanowires on quartz/silica glass

Recently, large-area quartz/silica substrates have also attracted attention by the III-nitride nanowire research community. These low-cost, scalable, and amorphous substrates can withstand temperatures of up to 1000 °C, which is high enough for nitride growth. They also have excellent optical transparency from the visible to UV wavelength region [199].

In 2016, Kumaresan et al. reported well-controlled GaN nanowire growth on non-crystalline silica substrates using plasma-assisted MBE [200]. Mulyo et al. further optimized the process, producing nanowires on fused silica glass that showed no threading dislocations, stacking faults, or twinning [201]. In this process, a Si₃N₄ intermediate layer with ABC stacking order is formed at the interface with the glass.

By combining MBE and MOCVD, Bae et al. grew high-quality GaN nanorods on quartz substrates. The MBE process was used to grow a relatively flat GaN nanograins buffer. The GaN nanorods were then grown selectively by MOCVD using a dielectric mask [202]. We have also demonstrated the growth of InGaN/GaN nanowires on amorphous quartz substrates using MBE (Fig. 28). A TiN/Ti interlayer was used to facilitate the growth. The fabricated LEDs based on the nanowire-on-quartz platform were applied in tunable correlated color temperature white light generation when mixing when red, green, and blue laser as demonstrated in the paper [203].

4. Challenges and problems

Although remarkable progress in the growth, characterization, and device demonstration has been made in nitride nanowire research, problems still remain that hinder the use of these structures in real applications. For example, to avoid metal contamination, a

| Emission Wavelength | Active region material(s) | Substrate | Growth technique | Year | Reference |
|---------------------|---------------------------|-----------|-----------------|------|-----------|
| 380 nm              | GaN                       | Graphite  | CVD             | 2013 | [189]     |
| 437 nm              | InGaN/GaN LED             | Graphene  | MOCVD           | 2014 | [190]     |
| 365 nm              | n-GaN                     | Graphene  | MOCVD           | 2015 | [191]     |
| 365 nm              | n-GaN                     | Graphene  | MOCVD           | 2015 | [192]     |
| 365 nm              | GaN                       | Graphene  | MOCVD           | 2016 | [194]     |
| 357 nm              | GaN                       | Graphene  | MBE             | 2016 | [195]     |
| 357 nm              | n-GaN                     | Graphene  | MOCVD           | 2017 | [196]     |
| 470 and 635 nm      | InGaN/GaN                 | MoS₂      | MBE             | 2017 | [198]     |

Fig. 27. (a) Typical L–I–V characteristics of the InGaN/GaN nanowire LED on MoS₂/Mo. (b) The electroluminescence spectra of the LEDs with different indium composition. The inset shows optical microscope images of the illuminated blue and yellow LEDs. (c) Schematic of the flexible LED releasing from the metal. Reproduced with permission. Ref. [198] Copyright 2017, The Royal Society of Chemistry. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
A catalyst-free approach to growing III-nitride nanowires is preferable. However, this method has its drawbacks, including a lack of control over the size, length, and position of the nanowires depending on the growth conditions [35,204]. Nanowire arrays grown in this fashion also have a lower active volume per unit area compared to thin films, and defects are generated along the coalesced sidewalls when the nanowires are highly packed.

Several approaches have been proposed to circumvent these issues. Among these are self-assembly of nanowires on patterned templates and the use of nucleation centers [205,206]. SAG is also an important fabrication technology because it provides better control of nanowire geometry, such as diameter, height, and position. For example, a GaN buffer layer using a patterned titanium mask was reported to selectively grow GaN nanocolumns at very high temperatures (above 900 °C) and high III/V ratios [70,71,207,208]. Schumann et al. optimized their catalyst-free MBE growth conditions and mask design to obtain SAG of GaN nanowires by varying the patterning layout, gallium flux, and substrate temperature [209]. To obtain superior nanowire growth, Jung et al. employed pulse-mode MOCVD to synthesize GaN nanowires. In their experiments, they patterned the c-plane GaN substrate with a SiO2 mask, controlled the growth parameters, such as substrate temperature and precursor injection durations, and succeeded in obtaining uniform GaN nanowires in terms of diameter, length, and location [210]. Mi et al. successfully controlled the coalescence of AlGaN nanowires and obtained nearly dislocation-free semi-polar AlGaN templates on a patterned sapphire substrate using e-beam lithography (Fig. 29) [211].

Although we have methods available to solve the issue of nanowire growth uniformity, they are time-consuming for practical applications because of the techniques used for patterning the substrates. Thus it is necessary to develop mask-less growth techniques for the scalable production of uniform nanowire arrays. Additionally, more study is needed on how to change surface conditions to encourage uniform nucleation and control nanowire growth.

Additionally, a more fundamental understanding of the growth mechanism and properties of nitride nanowires is needed. Although some researchers report defect-free growth of these materials, others observed the formation of stacking faults [212]. We need to understand the correlation between the formation of defects and the operation of the growth mechanism on different substrates. Moreover, the strain status in nanowires is very important for their optical properties and device applications. Although strain can be

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**Fig. 28.** Method for the fabrication of InGaN/GaN nanowire LEDs on quartz. Reproduced with permission. Ref. [203] Copyright 2018, SpringerOpen.

**Fig. 29.** (a) Schematic of the SAG process on patterned GaN template substrates. (b) SEM image of GaN nanowires. Reproduced with permission. Ref. [211] Copyright 2016, John Wiley and Sons.
relaxed through the surface, there is still no detailed study on strain for nanowires, especially in three dimensions. Answering these questions will rely on new techniques in electron microscopy and X-ray diffraction to explore the effects of strain and defects on these materials at the atomic scale. Although passivation has been studied to improve the efficiency of nanowire devices, it is necessary to develop enhanced methods to achieve electrical and dangling bond passivation, and improve light extraction using materials with proper refractive indexes.

Moreover, for future nanowire device applications, such as high-performance lasers, it will be necessary to combine both MBE and MOCVD techniques to take advantage of the high growth rate for thick cladding layers of lasers using MOCVD and the high crystal quality of the active layer produced by MBE growth. The current nanowire growth technology only guarantees single color emission from a given nanowire array. Meanwhile, SAG and multi-step growth have been applied to achieve efficient and smart light mixing to produce multi-colored lights (Fig. 30) [213,214]. A focus for future research will be achieving multiple wavelengths from a single growth of nanowires. Currently, most fabrication methods require complicated processes, such as filling material deposition, etching, and top contact deposition. A simpler fabrication technique for LEDs, lasers, etc., will improve the throughput for industry while ensuring high current injection efficiency with good electrical contact.

5. Summary and perspectives

To summarize, we have reviewed recent advances in III-nitride nanowire research, including different nanowire growth techniques, growth conditions and mechanisms, the adoption of various substrates, and methods of nanowire characterization. Catalyst-free growth techniques for GaN nanowires dominate the current growth technology, utilizing the MBE technique under nitrogen-rich conditions. To provide a broader understanding of the field, we have detailed various examples of MBE and MOCVD growth of nanowires. Additionally, the growth mechanisms of these materials were discussed, from nucleation to vertical growth, both in terms of kinetic and thermodynamic effects. We have further demonstrated that III-nitride nanowires can be used to construct various device platforms when grown on unconventional substrates, and have demonstrated their application in LEDs, photodetectors, lasers, solar cells, and photoelectrodes. However, more research is still necessary to improve fundamental understanding and promote the device application of these novel materials.

With further development in advanced growth and characterization, nanowire arrays will find practical applications in high-power optoelectronics, displays, energy conversion and green technologies, single-photon emitters, quantum computing, and high-speed electronics. Such nanoscale devices will be essential for realizing ultra-low profile displays on both flexible and rigid substrates.

Fig. 30. (a) Schematic of multi-colored nanowire LEDs. (b) Schematic of an individual nanowire LED. (c) Electroluminescence spectra of nanowire LED subpixels. (d) The electroluminescence spectra of a triple-color LED pixel injected at various continuous wave currents. Reproduced with permission. Ref. [213,214] Copyright 2014, Optical Society of America. Copyright 2016, SPIE. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Moving forward, there is potential for employing nanowires in multiple cross-disciplinary applications, such as visible-light communications, bio-sensing, and “wireless” solar water-splitting devices, as well as photodetection and sensing in high-temperature, harsh environments, by leveraging the chemical stability of high-quality nitride nanowires, the large specific surface areas of nanowires, and the lift-off ready nature of nanowire structures for substrate reuse.

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