Nanowire Micro-LEDs for Augmented Reality and Virtual Reality (AR/VR) Displays

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Abstract

We report on high efficiency InGaN nanowire-based micro and nanoscale light emitting diodes (LEDs). We show that record-high efficiency and highly directional emissions can be achieved with red and green submicron nanowire micro-LEDs. Such LEDs are critical for augmented reality displays which require both efficiency and high optical throughput.

Author Keywords

InGaN; micro-LED; nanowires; epitaxy.

1. Introduction

Micro and nanoscale optoelectronic devices, especially micro-LEDs with dimensions as small as one micrometer, are viewed as the foundation of emerging technologies required for augmented and virtual reality (AR/VR) displays. While conventional broad area multiple quantum well (MQW) LED devices, including those based on InGaN and AlInGaP, have been demonstrated with high efficiency across the entire visible spectrum, the efficiency of micro-LEDs decreases drastically with reducing dimensions, leading to the so-called *efficiency cliff*. As shown in **Figure 1** [1, 2, 11], typical devices, especially those with long-wavelength emission, having lateral dimensions below 10 μm fall below 1% external quantum efficiency, hindering their commercial applications. Factors that contribute to the low efficiency include i) high nonradiative surface recombination resulting from damage induced by the plasma etching of conventional top-down MQW devices, and ii) degraded p-type contact due to plasma etching. These issues are especially critical for InGaN based micro-LEDs operating at longer wavelengths (e.g., red), which further suffers from the low internal quantum efficiency (IQE) due to a higher indium composition and the resulting extensive defect formation.

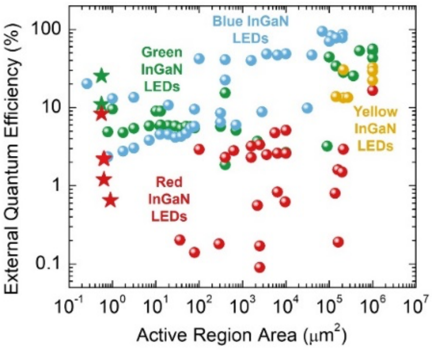

Figure 1. External quantum efficiency (EQE) for different active region areas with different emission wavelengths. The star data points mark efficiencies achieved for red and green submicron nanowire LEDs [1, 2, 11].

These critical issues can be fundamentally addressed by utilizing a bottom-up growth of nanostructures, which, in principle, can eliminate the use of plasma etching of the device active region [3], thereby circumventing some of key issues associated with top-down devices. This method resulted in nanostructure-based micro-LED devices that demonstrated record external quantum efficiencies (EQE), marked by the red and green stars on Figure 1, significantly higher than those fabricated with top-down techniques. Previously, nanostructures have been shown to be nearly defect-free, with enhanced strain relaxation and reduced quantum-confined Stark effect, that are crucial to overcome the efficiency bottleneck of green and red-emitting InGaN devices [4]. Selective area growth (SAG) enables the growth of nanostructures with fixed dimensions, position, and morphology, which is ideally suited for the fabrication of high performance devices. Recent studies have further revealed another unique advantage of epitaxial nanostructures: The emission wavelengths of the quantum-confined nanostructures can be tuned by selecting their dimensions in addition to variations in the growth parameters, allowing for further precision in micro-LED epitaxy [5]. The arrangement of the nanostructures can also enable optical engineering by forming photonic crystals, which can increase light extraction, enable guided modes of light for highly directional emission and reduce the full-width half maximum (FWHM) of the emission [6].

2. Experiment

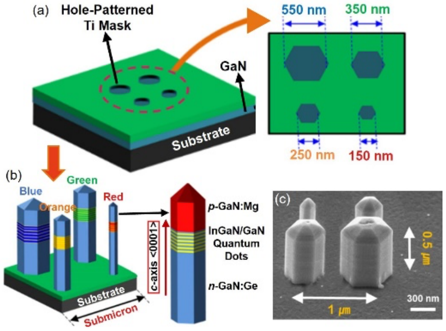

Figure 2. (a) Schematic of the patterning for SAG. (b) Schematic of nanowires grown on the openings. (c) SEM image of grown nanowires. Reprinted with permission from: Ra Y.H. et al. Full-color single nanowire pixels for projection displays. *Nano Letters,* vol. 16, no. 7, pp. 4608–4615, 2016. Copyright 2016 American Chemical Society. [6].

As shown in **Figure 2**, we used plasma-assisted molecular beam epitaxy (PA-MBE) to grow InGaN/GaN nanowire arrays on a variety of substrates, including sapphire and Si. For SAG, a growth mask is needed. In our studies, a Ti metal mask was used for selectivity, into which openings controlling the nanostructure dimensions were defined using electron-beam lithography and reactive ion etching (RIE). The Ti layer was nitridated prior to nanowire growth. A schematic of the patterning process is shown in **Figure 2(a)** and **(b)**, for the growth of nanowires with different dimensions to support the realization of monolithically multi-color LEDs on a single substrate. A scanning electron microscope (SEM) image of such nanowires is shown in **Figure 2(c)**.

For the nanowire devices, at first ~500 nm thick Si-doped n-GaN was grown at a relatively high substrate temperature to ensure selectivity. **Figure 3(a)** shows an SEM image of an array of nanowires displaying high selectivity and uniformity. The indium composition and therefore the emission wavelengths in the active region was controlled by tuning the Ga and In metal fluxes, as well as the substrate temperature. **Figure 3(b)** shows the variation of emission from blue-red wavelengths for nanowires grown using different Ga/In flux ratios and/or different nanowire design parameters. Finally, a p-GaN layer was grown over the active region.

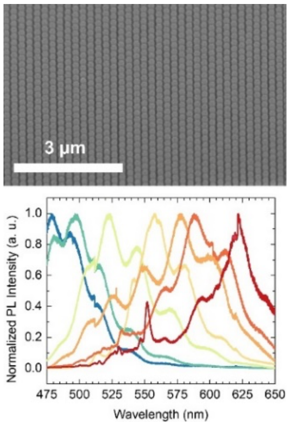

Figure 3. (a) Large area SEM image of a nanowire array. (b) PL spectra measured for different InGaN/GaN nanowires covering the visible spectrum [11].

The device fabrication process involves the use of standard optical lithography, dry and wet etching, contact metallization and annealing techniques. Firstly, atomic layer deposition (ALD) of an Al_2O_3 layer was used to insulate the gaps in between the nanowires. RIE was used to etch-back for exposing the top p-GaN, and then a thick SiO_2 layer was deposited using plasma-enhanced chemical vapor deposition (PECVD) to provide further passivation and planarization. Current injection windows were defined in the SiO_2 layer using stepper lithography and RIE. Finally, metal contacts were deposited and annealed for electrical injection.

3. Results and Discussion

Green micro-LED fabrication and results: High-efficiency N-polar green micro-LEDs utilizing a multiple quantum disk active region [7] were grown and fabricated, with results shown in **Figure 4**. **Figure 4(a)** plots the J-V of the device, showing a turn-on voltage ~4.5 V, with relatively low reverse leakage. The inset shows an SEM image of a current injection window that defined the active area of the device. The electroluminescence (EL) spectra for the device, measured at different injection currents are plotted in **Figure 4(b)**, showing a peak at ~530 nm. The variation of the output power measured for different injection currents is plotted in the L-I characteristics shown in **Figure 4(c)**. The corresponding EQE as a function of current is plotted in **Figure 4(d)**. The EQE peaks at ~11% at a current density of 0.83 A/cm^2. It is noticed that the EQE peaks at a low current density, which suggests that i) the device has low Shockley-Read-Hall (SRH) recombination, and ii) the device has relatively strong carrier overflow (or Auger recombination) related third-order carrier loss effect. The reduced SRH recombination is consistent with the reduced surface recombination from the bottom-up fabrication technique. At present, we are working on the optimization of the green micro-LED structure, by carefully designing and engineering the nanowire dimensions, quantum confinement, and polarity for improving the excitonic recombination within the active region and reducing higher order carrier loss effects.

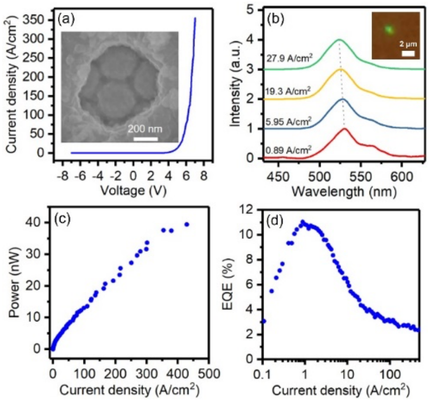

Figure 4. (a) J-V characteristics of a green emitting submicron nanowire LED. The inset shows an SEM image of the current injection window for the device. (b) EL spectra of the device. The inset shows the device under operation. Variation of (c) output power and (d) EQE with current density. Reprinted with permission from X. Liu *et al*, "N-polar InGaN Nanowires: Breaking the Efficiency Bottleneck of Nano and Micro LEDs," *Photonics Research,* vol. 10, no. 2, pp. 587-593, 2021. Copyright 2022 Chinese Laser Press [7].

Red micro-LED fabrication: Our studies have shown that N-polar nanostructures possess some important advantages for achieving high efficiency micro-LEDs. The N-polar bottom-up micro-LEDs were also extended to even longer wavelengths in the red [1]. In order to reduce defect distribution around the active region related to the large lattice mismatch between InN and GaN, an *in-situ* anneal at a temperature 50 ˚C above the growth temperature was incorporated to improve the luminescence from the active region by an order of magnitude.

The red-emitting micro-LEDs were fabricated utilizing approaches similar to those of the green micro-LEDs, and **Figure 5(a)** shows the J-V characteristics of a 750 nm × 750 nm area device. The EL spectra plotted in **Figure 5(b)** show a ~620 nm peak at low injection currents. The corresponding EQE plotted for varying current injection are in **Figure 5(c)** reaching a peak of ~1.2% at ~0.5 A/cm^2 for direct on-wafer measurement. Recently, we also included an InGaN/GaN short-period superlattice (SPSL) beneath the red-emitting active region to relax the strain and defect distribution and thereby further increase the performance red-emitting devices, through which we reached a peak EQE of 2.2% [8]. Further optimization of the doping, device design, and fabrication process are presently in progress to achieve enhanced performance.

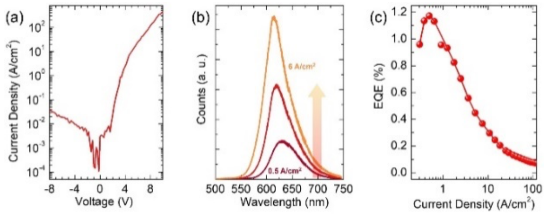

Figure 5. (a) J-V characteristics of the red submicron LED. (b) EL spectra of the InGaN/GaN micro-LED measured at different injection currents. (c) Variation of the EQE vs. injection current density. Reprinted with permission from A. Pandey *et al*, "N-polar InGaN/GaN nanowires: overcoming the efficiency cliff of red-emitting micro-LEDs," *Photonics Research,* vol. 10, no. 4, pp. 1107-1116, 2022. Copyright 2022 Chinese Laser Press [1].

The large FWHM of long-wavelength (green and red) InGaN LEDs (due to indium phase separation), combined with the wavelength-shift caused by the quantum-confined Stark effect (QCSE) can distort the spectral purity of the emission, affecting the perceived color [9]. We have shown such an issue can be potentially overcome by developing nanowire photonic crystal LEDs. **Figure 6(a)** plots the EL spectra measured for a 5 µm × 5 µm photonic nanocrystal (PhNC) micro-LED emitting at ~548 nm [10]. The narrow peak shown in the emission spectra is stable (in terms of both the spectral linewidth and peak position) over nearly four orders of magnitude of the injection current. The relative EQE plotted in **Figure 6(b)**, peaks at ~5 A/cm^2 with a relatively low efficiency droop of ~30% at 100 A/cm^2.

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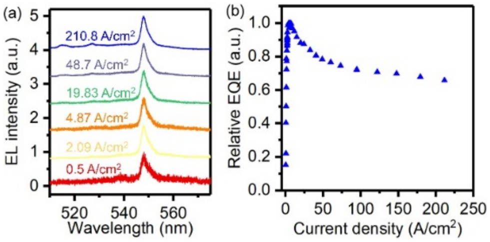

Figure 6. (a) EL spectra of PhNC micro-LED measured at different injection currents. (b) Variation of the EQE vs. injection current density. Reprinted from Liu X et al. Micrometer scale InGaN green light emitting diodes with ultra-stable operation. *Applied Physics Letters,* vol. 117, no. 1, p. 011104, 2020, with the permission of AIP Publishing [10].

4. Conclusions

Our work has shown that bottom-up micro-LEDs with nanostructures can be utilized for overcoming the efficiency cliff of micro and nano-scale LEDs. We have demonstrated record high efficiencies for green and red LED devices, with lateral dimensions below a micron, that have so far been impossible to achieve in top-down devices. Nanostructures avoid several major challenges associated with top-down devices, while presenting other advantages such as strain relaxation, higher doping, and reduced QCSE effect, making them the ideal for longer wavelength LEDs. The special technique of SAG can further extend their applications by potentially allowing stable and narrow linewidths, as well as the possibility of monolithic integration of several colors on a single chip. Moreover, such nanostructure-based micro-LEDs can be monolithically grown directly on Si substrate, potentially enabling seamless integration with CMOS electronics [12]. These results show that epitaxial nanostructures can be the preferred platform for future VR/AR as well as other micro-scale and smaller optoelectronic applications.

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Disclosures. Some intellectual property related to this work was licensed to NS Nanotech Inc., which was co-founded by Z. Mi. The University of Michigan and Z. Mi have a financial interest in NS Nanotech.

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