# Size matters: Why nanowire micro-LEDs are the choice of next-generation mobile displays and virtual reality

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## ABSTRACT

*We report on the demonstration of high efficiency InGaN nanowire-based micro and nanoscale light emitting diodes (LEDs). The emission wavelengths can be controllably tuned in the visible spectrum by varying the nanowire dimensions. We show that nanowire micro-LEDs with high efficiency and highly directional emission can be achieved. Moreover, by controlling the size and spacing, highly stable emission with narrow spectral linewidth can be realized in nanowire photonic crystal LED structures.*

## 1 Introduction

Micro and nanoscale optoelectronic devices are projected to be the foundation of emerging technologies such as augmented and virtual reality. While conventional multiple quantum well InGaN devices have been demonstrated with emission across the entire visible spectrum, to date, the efficiency of micro-LEDs is significantly lower than large-area devices, as shown in Figure 1 [1, 2], falling below 1% for typical devices having lateral dimensions below 10 µm, making their application in commercial products impractical. The primary cause of the low efficiency has been attributed to the increased surface recombination as a result of the damage induced by the plasma etching of conventional top-down quantum well LEDs. This problem is compounded for InGaN devices emitting at longer wavelengths, that require a higher indium composition.

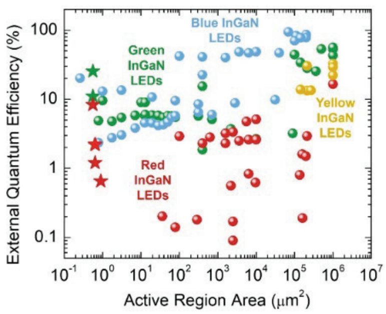


**Fig. 1 External quantum efficiency (EQE) for different active region areas with different emission wavelengths. The star data points are our work.**

In this context, bottom-up nanostructures can circumvent the problems associated with top-down devices due to their unique fabrication methodology which avoids plasma etching of the device active region [3]. Furthermore, they have been shown to be nearly defect-free, with enhanced strain relaxation, benefitting the performance of green and red emitting devices [4]. Using the technique of selective area epitaxy (SAE), it is also possible to grow the nanostructures with controlled dimensions and spacings, and it has been shown that the indium incorporation, and hence the emission wavelength of the nanostructures depends strongly on their dimensions, enabling another degree of control over the fabrication of micro-LEDs [5]. In addition, the nanostructures can be arranged to create photonic crystals which can increase the light extraction, enable guided modes of light that allow for highly directional emission and greatly reduce the linewidth of emission [6].

## 2 Experiment

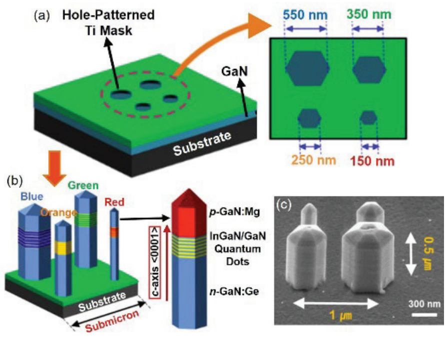


**Fig. 2 (a) Schematic of the patterning for SAE. (b) Schematic of nanowires grown on the openings. (c) SEM image of grown nanowires. Reprinted with permission from Y.-H. Ra *et al.*, "Full-color single nanowire pixels for projection displays," *Nano Letters,* vol. 16, no. 7, pp. 4608–4615, 2016. Copyright 2016 American Chemical Society [119]. [6].**

We used plasma-assisted molecular beam epitaxy (PA-MBE) to grow InGaN/GaN nanowire arrays. SAE was performed using a Ti metal mask on GaN substrates, into which openings for the growth of nanowires were defined with electron beam lithography, and then etched using reactive ion etching. A schematic of the patterning process is shown in Fig. 2(a), and the monolithic growth of multi-color LEDs is schematically shown in Fig. 2(b). A scanning electron microscope (SEM) image of such nanowires is shown in Fig. 2(c).

To ensure a high degree of selectivity with the Ti mask, the nanowire growth was initiated with an initial ~500 nm thick Si-doped n-GaN layer grown. Using this technique, we demonstrated the growth of highly uniform arrays of nanowires, shown in a large area SEM image in Fig. 3(a). The indium composition in the active region was modulated by tuning the fluxes of Ga and In. By controlling the ratios of the metal fluxes, we can attain emission covering the entire visible spectrum, shown in Fig. 3(b). Finally, a Mg-doped p-GaN layer was grown over the active region to form the electrical contacts for micro-LED devices.

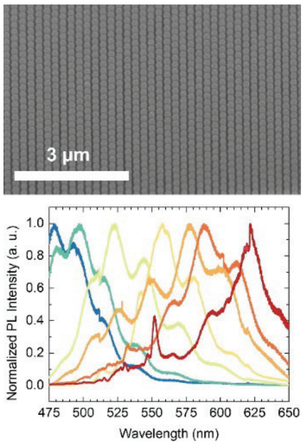


**Fig. 3 (a) Large area SEM image of a nanowire array. (b) PL spectra measured for different InGaN/GaN nanowires covering the visible spectrum.**

To fabricate the nanowires into micro-LED devices, first the nanowires were passivated with an insulating $Al_2O_3$ layer deposited by atomic layer deposition (ALD). This layer was then etched back using reactive ion etching (RIE) to expose the top p-GaN contact of the nanowires. A thick $SiO_2$ layer was then deposited using plasma-enhanced chemical vapor deposition (PECVD). Etch windows were defined in the $SiO_2$ layer using lithography, and the dielectric within them was etched away using RIE. This is followed by a metallization step to define electrical contacts for devices.

## 3 Results and Discussion

We fabricated high-efficiency N-polar green micro-LEDs utilizing a multiple quantum disk active region [7]. The J-V characteristics of the device are presented in Fig. 4(a), showing negligible reverse bias leakage current and a turn-on voltage ~4.5 V. The inset shows an SEM image of a current injection window that defined the area of the fabricated micro-LED. We measured the electroluminescence (EL) for the device at different injection currents, displaying an emission peak at ~530 nm. The measured EL spectra are plotted in Fig. 4(b). The output power of the device was collected through the back of the sapphire substrate, with the L-I characteristics plotted in Fig. 4(c). The calculated EQE at different current densities is plotted in Fig. 4(d), reaching a maximum value of ~11% at 0.83 A/cm$^2$. The efficiency peak at low current density indicates low levels of Shockley-Read-Hall (SRH) recombination, which proves that this method minimalizes the deleterious impact of surface recombination. Further optimization of the green micro-LED structure, by carefully designing the nanowire dimensions has also enabled devices with an even greater peak EQE of ~25.3%, attained through the effective excitonic recombination of carriers under low injection [8].

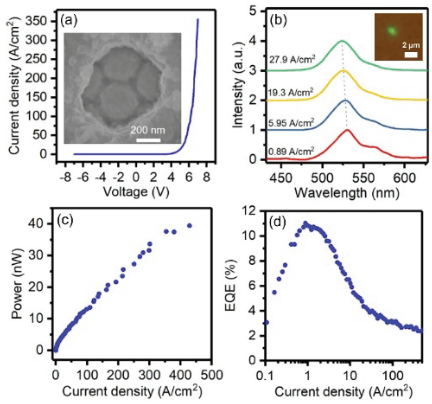


**Fig. 4 (a) J-V characteristics of a green emitting submicron nanowire LED. The inset shows an SEM image of the current injection window for the device. (b) EL spectra of the device. The inset shows the device under operation. Variation of (c) output power and (d) EQE with current density. Reprinted 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].**

We also fabricated high performance red micro-LEDs utilizing the bottom-up growth approach [1]. To attain high intensity emission in the red wavelength range, a high indium composition InGaN segment was annealed *in-situ* at a temperature 50 ˚C above the growth temperature. This annealing process dramatically increased the photoluminescence intensity from the active region by over an order of magnitude. The devices with the annealed active region were then fabricated using a similar process as for the green micro-LEDs. Shown in Fig. 5(a) is the J-V characteristic of a fabricated micro-LED with an area of 750 nm × 750 nm. EL spectra measured for varying injection currents are plotted in Fig. 5(b). The device shows strong emission at ~620 nm under low injection currents. Further, the EQE measured with varying injection currents is plotted in Fig. 5(c) reaching a peak value of ~1.2% at a low current density of ~0.5 A/cm$^2$. We have further built upon this work by introducing a short-period superlattice (SPSL) beneath the active region to relax the strain and increase the performance red-emitting devices, enabling the realization of red-emitting micro-LEDs having a peak EQE of 2.2%.

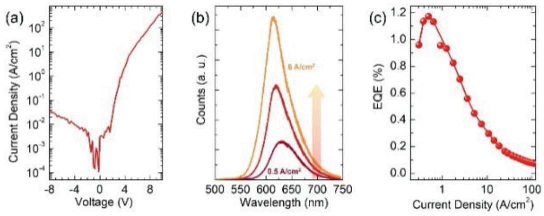


**Fig. 5 (a) J-V characteristics of the red submicron LED. (b) EL spectra of the InGaN/GaN micro-LED measured at different injection currents. (c) Variation of the EQE vs. injection current density [1].**

A major concern regarding long-wavelength InGaN LEDs is the large full-width half maximum of the emission peaks, which can distort the spectral purity of the emitted light [9]. Further, the quantum-confined Stark effect (QCSE) results in a shift of the emission peak for different injection currents. SAE enables growing photonic crystals through which light can be guided, enabling sharp emission linewidths. Figure 6(a) shows the EL spectra measured for a 5 μm × 5 μm photonic nanocrystal (PhNC) micro-LED emitting in the green wavelength range, at ~548 nm [10]. A sharp mode in the EL spectrum is visible, that remains stable over nearly four orders of magnitude of the injection current. The relative EQE of the device is plotted in Fig. 6(b), showing a peak at ~5 A/cm$^2$ and a relatively low efficiency droop of ~30% at 100 A/cm$^2$.

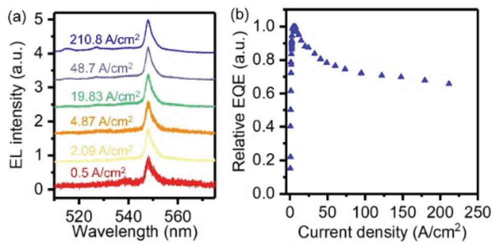


**Fig. 6 (a) EL spectra of PhNC micro-LED measured at different injection currents. (b) Variation of the EQE vs. injection current density. Reprinted from X. Liu *et al*, "Micrometer scale InGaN green light emitting diodes with ultra-stable operation," *Applied Physics Letters*, vol. 117, no. 1, p. 011104,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

## 4 Conclusions

Through our work on nanowire-based micro-LEDs, we have demonstrated record high efficiencies for green and red LEDs, at sub-micron scales, which are even smaller than those attainable with conventional top-down approaches. The unique fabrication methodology, high strain relaxation and efficient carrier conduction in these nanostructures can solve several fundamental challenges currently facing small-area optoelectronic devices. By combining this bottom-up approach with SAE we can further realize highly uniform devices and enable monolithic integration of different color pixels, while attaining highly stable and narrow linewidth emission using photonic crystals. These results exemplify the revolutionizing capability of nanowires for micron-scale, and smaller, optoelectronics.

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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.

**References**

[1] A. Pandey, Y. Malhotra, P. Wang, K. Sun, X. Liu, and Z. Mi, "N-polar InGaN/GaN nanowires: overcoming the efficiency cliff of red-emitting micro-LEDs," *Photonics Research,* vol. 10, no. 4, pp. 1107-1116, 2022.

[2] A. Pandey and Z. Mi, "III-Nitride Nanostructures for High Efficiency Micro-LEDs and Ultraviolet Optoelectronics," *IEEE Journal of Quantum Electronics,* 2022.

[3] P. Tian *et al.*, "Size-dependent efficiency and efficiency droop of blue InGaN micro-light emitting diodes," *Applied Physics Letters,* vol. 101, no. 23, p. 231110, 2012.

[4] G. Tourbot *et al.*, "Structural and optical properties of InGaN/GaN nanowire heterostructures grown by PA-MBE," *Nanotechnology,* vol. 22, no. 7, p. 075601, 2011.

[5] H. Sekiguchi, K. Kishino, and A. Kikuchi, "Emission color control from blue to red with nanocolumn diameter of InGaN/GaN nanocolumn arrays grown on same substrate," *Applied physics letters,* vol. 96, no. 23, p. 231104, 2010.

[6] Y. H. Ra, R. T. Rashid, X. Liu, J. Lee, and Z. Mi, "Scalable nanowire photonic crystals: Molding the light emission of InGaN," *Advanced Functional Materials,* vol. 27, no. 38, p. 1702364, 2017.

[7] 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, 2022.

[8] A. Pandey *et al.*, "An Ultrahigh Efficiency Excitonic Micro-LED," (submitted), 2022.

[9] Y. Robin, M. Pristovsek, H. Amano, F. Oehler, R. Oliver, and C. Humphreys, "What is red? On the chromaticity of orange-red InGaN/GaN based LEDs," *Journal of Applied Physics,* vol. 124, no. 18, p. 183102, 2018.

[10] X. Liu, Y. Wu, Y. Malhotra, Y. Sun, and Z. Mi, "Micrometer scale InGaN green light emitting diodes with ultra-stable operation," *Applied Physics Letters,* vol. 117, no. 1, p. 011104, 2020.