# Toward Ultrahigh Efficiency GaN Nano and Micro Full-Color LEDs

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## ABSTRACT

*Using the selective area epitaxy technique, we have demonstrated nanowire emitters with controlled diameter, position, and emission wavelength. Furthermore, monolithic integration of multicolor emission and photonic crystal structure are realized, which allows for ultimately small multicolor nano-LEDs and micro-LEDs with emission properties tailored by the photonic crystal, as well as surface emitting lasers.*

## 1 INTRODUCTION

Micro-light emitting diodes (LEDs) with high brightness and high efficiency in the visible spectrum are critical for a broad range of applications including mobile displays, virtual/mixed/augmented reality devices, bio-sensing, and communications.[1-5] Nevertheless, the realization of high efficiency InGaN micro-LEDs remains a challenge, particularly in the green and red wavelengths. The efficiency of micro-LEDs has been mainly limited by the formation of high defect densities and phase separation upon high indium content, surface non-radiative recombination due to dry-etch induced surface damage and poor current injection.[6-10] The quantum-confined Stark effect due to polarization field further leads to varying emission wavelengths with increasing current.[11, 12]

The fabrication and performance of micro-LEDs by top-down etching has been extensively studied. Jordan et al.[13] revealed a close correlation between the mesa size of micro-LEDs fabricated by top-down approach and peak EQE. A peak EQE of 12-13.5% for blue (455-470 nm) micro-LEDs with a mesa diameter of 2 µm was achieved using wet etching and dielectric passivation by Ryan et al.,[14] which was intended to minimize the surface nonradiative recombination. Neutral-beam-etching technique and regrowth are developed to maintain a similar internal quantum efficiency as unetched quantum wells.[15] Besides top-down approach, bottom-up micro-LEDs and dislocation-free nanostructures have also been studied by us and other groups.[16-20] Using the nanocolumn structure formed by selective area epitaxy (SAE), Hiroto et al.[19] demonstrated monolithic integration of different photoluminescence colors from blue to red and Katsumi et al. further demonstrated multicolor integrated nanocolumn micro-LEDs as a route to micro-LED display.[20] By using a direct epitaxial approach on GaN template with a $SiO_2$ mask, Jie et al. realized green micro-LED arrays with an external quantum efficiency (EQE) of 6%.[21] Given the advantage in the dislocation-free material quality, the incorporation of indium owing to efficient strain relaxation, and efficient p-type Mg-dopant incorporation, we have performed detailed studies on the epitaxy and properties of nanowire structures and the performance of micro-LEDs.[3, 22-24]

## 2 EXPERIMENT

We use the SAE technique to grow nanowires, which requires the substrate to be patterned prior to growth. First, a 10 nm thick layer of Ti is deposited on a n-GaN-on-sapphire template. This Ti layer serves as the growth mask allowing for growth selectivity. Then electron beam lithography is performed to expose the designed pattern which is usually a triangle lattice of apertures of which the lattice constant and diameter are precisely designed and controlled. The exposed region is developed and subsequently dry etched using resist as the mask to reveal the n-GaN surface in the apertures. Resist stripper is used to remove the resist in a heated bath and thorough solvent clean is performed prior to epitaxial growth.

The epitaxial growth is conducted using a plasma-assisted molecular beam epitaxial system at a relative high temperature after careful tuning of the growth condition. The growth temperature is set sufficiently high to enhance the desorption of Ga adatoms and minimize the growth on Ti surface, while an overly high temperature may lead to a very low, undesirable growth rate. The Ga flux and the nitrogen flow rate are also optimized to minimize unwanted nucleation and growth on Ti surface. Due to the high desorption rate of In, InGaN is typically grown at a considerably reduced temperature under a N-rich condition to allow for In incorporation. By varying the growth temperature, the control over the incorporation of In is readily achieved to allow for different luminescence colors.

## 3 RESULTS

### 3.1 Multicolor single nanowire nano-LEDs

The incorporation of In is heavily dependent on the nanowire diameter, which is the direct consequence of surface migration dynamics of In atoms and Ga atoms. The In adatoms and Ga adatoms on nanowires have contributions from both direct impingement and surface migration. For single nanowires with large diameters, In atoms can desorb before reaching the center of the wire while Ga atoms have much longer migration length. The In incorporation on nanowires with large diameters is therefore reduced compared to nanowires with small diameters. The resultant luminescence color of single nanowires exhibits a blueshift with increasing diameter.

Patterned Ti mask consisting of apertures with different diameters is prepared using the process outlined in the experiment section as shown in Fig. 1(a).[3] The nanowires with different diameters formed by SAE are shown in Fig. 1(b).[3] It is seen that the diameters are well controlled as designed. The single nanowires samples are subsequently processed using standard planarization, lithography, and metallization to form single nanowire devices. The pixel, which includes four nanowire LEDs, exhibits emission wavelengths across nearly the entire visible spectrum on a single chip as shown in Fig. 1(c).[3] Such monolithic integration of full-color nano-LEDs pixels on the submicron scale offers a unique pathway to ultrahigh resolution and efficient micro-displays.

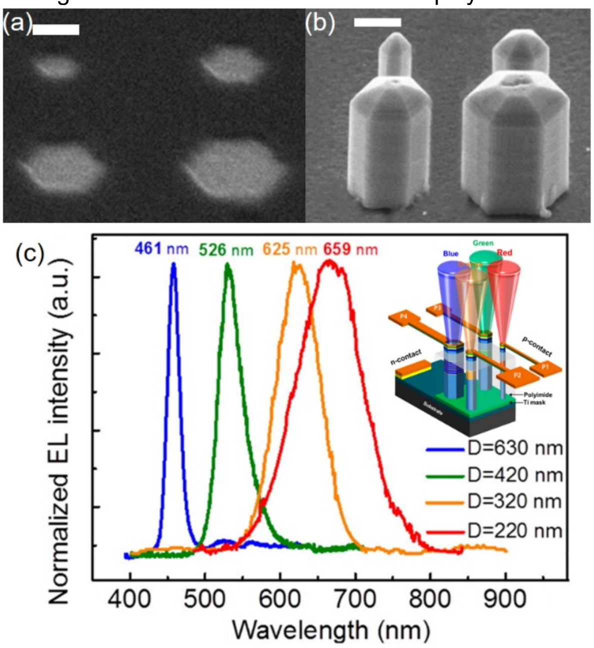


**Fig. 1 (a) SEM image of a GaN template with patterned Ti mask. The scale bar represents 250 nm. (b) The SEM image of nanowires formed by SAE. The scale bar represents 250 nm. (c) Electroluminescence spectra of a pixel consisting of four single nanowires. The inset is a schematic of the device.[3]**

### 3.2 Multicolor micro LEDs

As discussed above, the In incorporation depends on the nanowire diameter. When nanowires are densely arranged to form an array, the In content for larger diameters is higher as opposed to lower in the case of single nanowires. The supply of Ga becomes the dominant factor. Given a fixed lattice constant, larger diameter (or smaller spacing) indicates less Ga contribution from lateral surface migration as a result of shadowing by neighboring nanowires, which is also explained by Hiroto et al.[19] Such reduced Ga incorporation leads to a redshift with increasing diameter. Monolithically integrated multi-color micro-LEDs with a mesa size of 5 μm × 5 μm are demonstrated as shown in Fig. 2.

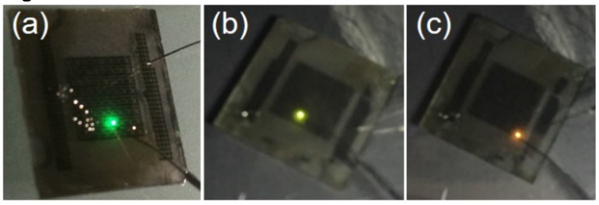


**Fig. 2 The photos of 5 μm × 5 μm micro-LEDs with (a) green, (b) yellow, and (c) orange emission.**

### 3.3 Ultrastable micro LEDs

By using photonic crystal structure, stable emission peak wavelength and directional emission have been previously reported for large area LEDs.[25] We further incorporated photonic crystal with micro-LEDs and demonstrated micro-LEDs with ultrastable operation. As shown in the bandstructure in Fig. 3(a), nanowires are arranged in a way that forms a photonic crystal structure which has the Γ point of the 4$^{th}$ band matching the emission spectrum of the active region.[23] Due to nearly negligible in-plane wavevector at the Γ point, the overall wavevector is along the vertical direction, which is expected to give vertical emission and narrow spectral linewidth. The micro-LEDs are fabricated and unique emission properties are measured as shown in Fig. 3(b).[23] The spectral linewidth, which remains only a couple of nanometers, is significantly narrower than that of conventional planar quantum well LEDs. Unlike conventional planar quantum well LEDs which commonly exhibit wavelength shift due to quantum-confined Stark effect, our micro-LEDs exhibit emission wavelengths dominated by photonic crystal structure, which remains the same over a wide range of injection currents. Directional emission with a divergence angle of ~10 degrees is also realized as shown in Fig. 3(c).[23] Such tailored emission properties and ultra-stable operation can greatly simplify the structure of optical systems and are ideally suited for near-eye micro-display applications.

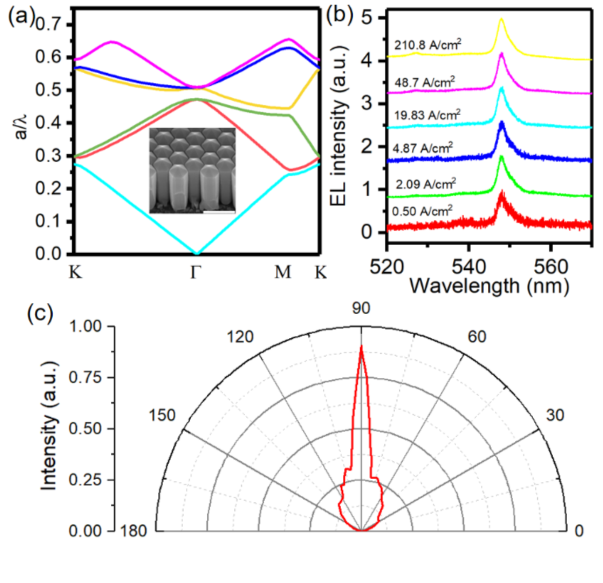


**Fig. 3 (a) Designed photonic bandstructure. The inset is the SEM image of the nanowire photonic crystal where the scale bar represents 500 nm. (b) Electroluminescence spectra of a nanowire photonic crystal micro-LED. (c) The far-field radiation pattern in a 10 nm spectral window at the peak wavelength.[23]**

### 3.4 Surface Emitting Laser Diodes

To date, it has remained challenging to achieve high performance surface emitting laser diodes in the visible or UV spectrum, largely due to the poor quality of GaN-based distributed Bragg reflectors (DBRs). DBR-free surface emitting lasers can be realized by exploiting the optical feedback at Γ point upon introducing optical confinement in the vertical direction. The optical confinement in the vertical direction is realized by the large thickness of low-index GaN cladding layers below and above the active region. In addition, Al is incorporated in the barrier layers in the active region to form an Al-rich shell minimizing the surface nonradiative recombination. The emission spectra are shown in Fig. 4(a).[24] The spectrum has a broad spontaneous peak at ~ 524 nm with a linewidth of ~30 nm below threshold. A strong lasing peak with a linewidth of ~0.8 nm emerges at ~523 nm as the current increases.

Lasing action is confirmed from the nonlinear increase in output power as shown in Fig. 4(b) and simultaneous reduction of spectral linewidths with increasing current as shown in Fig. 4(c) at an injection current of 400 A/cm$^2$.[24] The lasing action remains stable far above the threshold as shown in Fig. 4(d).[24] The threshold current density is much lower than previously reported GaN VCSELs, which is attributed to efficient optical feedback in the photonic crystal and high material quality.[26-28]

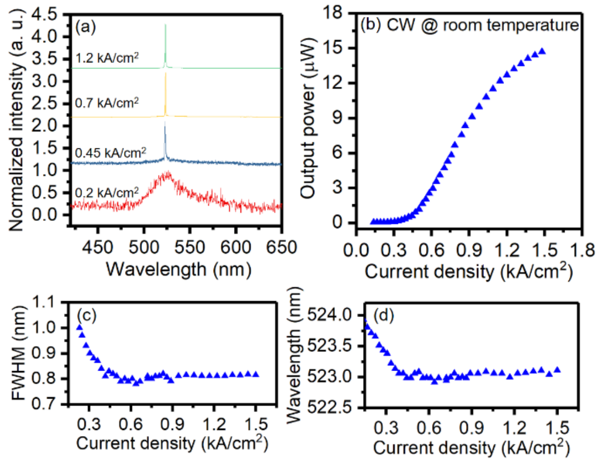


**Fig. 4 (a) Emission spectra below and above the threshold. Each spectrum is normalized by its peak intensity. Variations of (b) output intensity, (c) spectral linewidth, and (d) peak wavelength with injection current.[24]**

## 4 CONCLUSIONS

The nanowire structure as a versatile building block has demonstrated its huge potential for light sources suited for various scenarios, including nanoscale high density multicolor emitter arrays, light sources with ultrastable operation and special emission properties, and low threshold coherent light sources. It is expected that the efficiency of nanowire-based light emitters will be significant improved with further optimization in the epitaxy, device fabrication, and packaging. Moreover, the versatility offered by nanowires holds the promise for meeting the demands of the next generation of lighting and display devices and beyond.

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