Breaking the Efficiency Bottleneck of microLEDs Through Nanoscale and Excitonic Engineering

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***Abstract*—Light emitting diodes (LEDs) on the micrometer scale or smaller, also known as micro-LEDs, have been under intense investigations for their immense potential for various applications. In particular, the InGaN based III-nitride micro-LEDs have attracted much attention due to the many desirable materials properties such as wavelength tunability across the entire visible spectrum and high brightness. Yet, due to the lattice mismatch and a lack of intermiscibility between InN and GaN, it has remained challenging to achieve high efficiency green and red-emitting InGaN-based LEDs, especially at micro- and nano-scales. Here, we present recent progress on InGaN nanowire based green and red-emitting micro-LEDs. We show that nanoscale and excitonic engineering offers a promising path to address the efficiency cliff of micro/nano-scale LEDs. Our work points to pathways toward realization of a full-color, all-III-nitride micro-LED display.**

Keywords*—*micro-LED, selective area growth, III-nitride

I. Introduction

The performance of conventional optoelectronic devices, such as LEDs and laser diodes, is extremely sensitive to the presence of defects and dislocations. For these reasons, it has remained challenging to achieve high efficiency nanoscale LEDs and laser diodes. For example, while conventional broad area LEDs can exhibit external quantum efficiency (EQE) in the range of 80-100%, the EQE of submicron scale LEDs is often <1%, due to the dominant nonradiative surface recombination. The operation of conventional LEDs involves the radiative recombination of free electrons and holes in the active region. It is known that an exciton, a bound state of an electron and hole through strong Coulomb interaction, can drastically enhance the radiative recombination efficiency [1], which can be potentially exploited to make micro and nanoscale LEDs relatively immune from the presence of defects/traps. Recent studies have shown that the exciton oscillator strength can be increased by nearly two orders of magnitude in small size InGaN nanowires, due to efficient strain relaxation and enhanced electron-hole wavefunction overlap [2]. Here we demonstrate that the efficiency bottleneck of micro-LEDs can be fundamentally addressed by utilizing bottom-up III-nitride nanostructures. We report on the demonstration of micrometer scale green and red LEDs with an EQE of 25% and 8%, respectively, which are the highest values ever reported to the best of our knowledge for devices with lateral dimensions of 1 μm, or smaller. We employ selective area plasma-assisted molecular beam epitaxy as the material synthesis platform. Due to efficient strain relaxation, such bottom-up nanostructures are largely free of dislocations. By exploiting the large exciton binding energy and oscillator strength of quantum-confined InGaN nanostructures, we show that the EQE of a green-emitting micrometer scale LED can be dramatically improved from ~4% to >25%. The improved efficiency is attributed to the utilization of semipolar planes in strain-relaxed nanostructures to minimize polarization and quantum-confined Stark effect and the formation of nanoscale quantum-confinement to enhance electron-hole wavefunction overlap. We have further developed a new approach that included an InGaN/GaN short period superlattice together with an InGaN quantum dot active region to achieve high efficiency red emission. A maximum quantum efficiency of >8% was measured. Our studies offer a viable path to achieve high efficiency micrometer scale LEDs for a broad range of applications including mobile displays, virtual/augmented reality, biomedical sensing, and high-speed optical interconnects, that were difficult for conventional quantum well based LEDs.

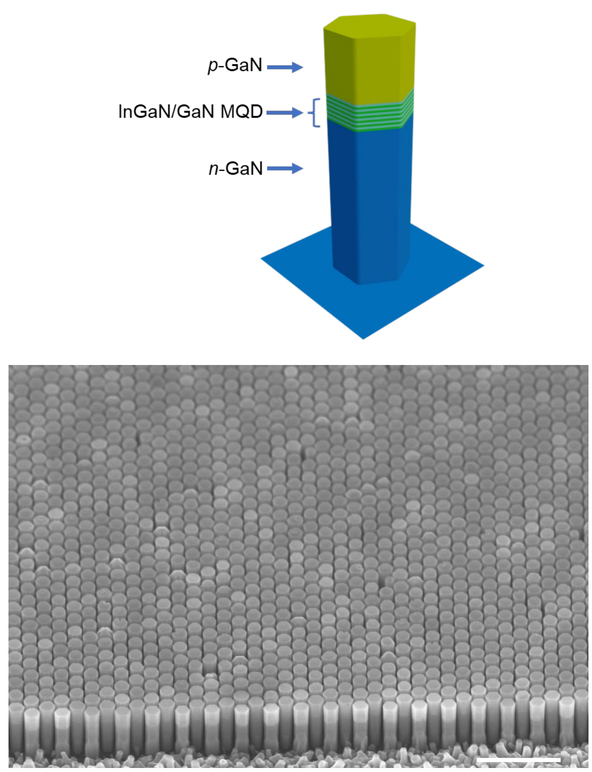

Fig. 1. Top: Schematic of a single nanowire LED. Bottom: Scanning electron micrograph of a nanowire array. Scale bar: 1 micrometer.

ISSN 0097-996X/25/5601-0331-$1.00 © 2025

II. Excitonic efficiency enhancements

Our bottom-up micro-LED devices comprise arrays of nanowires shown in Figure 1. Compared to traditional top-down micro-LED devices, the bottom-up nanowires form *in situ* during the device materials synthesis, such that the sidewalls of the active region segment remain free from etching damage. The diameters and positions of the nanowires can be precisely controlled by the design of the selective area growth mask. As shown in Fig. 2, we have observed significant device efficiency improvement for nanowire LEDs with enhanced excitonic effect [1], which is realized in small size, strain-relaxed nanowires. It is well known [4,5] that the quantum confinement effect can significantly enhance the excitonic binding energy in quantum wells, but this binding energy enhancement is countered by the built-in electric fields along the c-axis of the III-nitrides, which is the device growth axis, due to the material's spontaneous polarization and strain-induced piezoelectric polarization, which repel the electrons and holes from each other to form excitons. The exciton population density is significant to the device efficiency because excitonic emission is more efficient than traditional free-carrier radiative recombination at low current injection levels, partly because the former (i.e. excitonic emission) is linearly dependent on carrier density while the latter (i.e. free carrier radiative recombination) is quadratically dependent on carrier density.

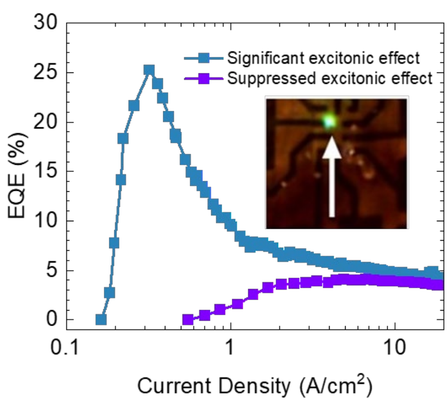

Fig. 2. Plot of external quantum efficiency (EQE) *vs.* current injection density of devices with significant and supprssed excitonic effect, respectively. Inset: optical micrograph of an operating green-emitting micro-LED [1].

Due to their small lateral dimensions, the bottom-up nanowires efficiently relieve the materials strain such that the built-in electric field (in the active region) is greatly reduced. Once the built-in electric field is sufficiently reduced, excitonic effects can be harvested to realize significant efficiency gain at low to moderate current injection levels, which are relevant for displays requiring low power, such as wearable AR/VR devices. It is worth noting that the EQE of both devices in Fig. 2 nearly coincides at high current injection levels (~10 A/cm^2), indicating that the stark contrast in efficiency at lower current injection levels is largely due to excitonic effects.

III. High efficiency red micro-LEDs

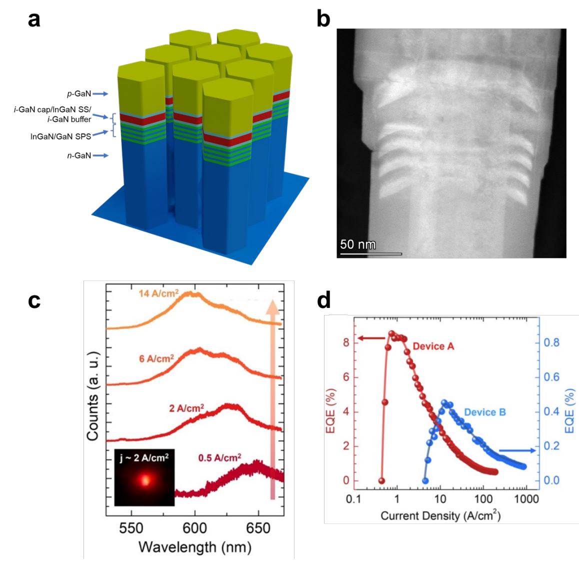

Fig. 3. High efficiency red emitting micro-LEDs. (a) Schematic of the nanowire design, which employs a short-period superlattice (SPS) that allows for high levels of In incorporation in the single segment (SS) active region. (b) High angle annular dark field scanning transmission electron micrograph, where the four layers of SPS InGaN and the single segment active region InGaN are clearly visible. (c) Electroluminescence spectra at various current injection levels. Inset: optical micrograph of the red-emitting device with 2 A/cm^2 injection current density. (d) The external quantum efficiency (EQE) of such red emitting μLED devices can reach >8%. Device A and Device B show the impact of growth conditions on device efficiency [7].

In addition to the green-emitting ones, red emitting III-nitride micro-LEDs have also been under investigation [6]. Efficient red emission for III-nitride devices is even more challenging than green emitting ones, since the level of indium incorporation required (for red emission) is significantly higher. Strain management is key to efficient indium incorporation, and our bottom-up nanowire array approach opens up an additional degree of freedom for strain relaxation compared to traditional epilayer device growth strategies. As shown in Fig. 3, with the incorporation of a short-period superlattice beneath the active region [7], the device, with a surface area ~1 μm^2, showed a peak EQE > 8% and spectral peak wavelength in the red regime.

IV. Conclusion

In summary, we have highlighted how the bottom-up selective area growth approach has opened up pathways to high efficiency micro-LEDs for emissions in both the green and the red wavelengths. With further innovations to improve device efficiency particularly for red-emitting InGaN micro-LEDs, the next-generation efficient and powerful solid-state displays based entirely on the III-nitride family will soon come to fruition.

V. Acknowledgements

This work was supported by NS Nanotech Inc.

Conflict of Interest: Some IP related to this work has been licensed to NS Nanotech, Inc., which was co-founded by Z. Mi. The University of Michigan and Mi have a financial interest in the company.

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