Highly Efficient GaN Based Micro-LEDs for High Resolution LED Displays

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ABSTRACT

The developments of high efficiency InGaN based micro-light-emitting diodes are discussed. Through novel epitaxial growth and processing, LED efficiencies as high as 33% EQE are achieved. The critical challenges of micro-LEDs: decreasing pixel size, making full-color emitters, and mass transfer technique are explored.

1 INTRODUCTION

We present state-of-the-art outstanding achievements in improving the external quantum efficiency of Micro-LEDs for the emerging high-quality display applications. Due to the miniature dimensions of Micro-LEDs, the key understandings and the significant device advancements to achieve excellent energy efficiency will be discussed. Through novel epitaxial growth and advanced semiconductor processing technologies, efficiency as high as 33% EQE are achieved for 20micron square blue III-nitride Micro-LEDs. Lastly, other critical challenges of Micro-LEDs, namely full-color scheme, decreasing pixel size and mass transfer technique, and their potential solutions are discussed.

2 RESULTS

Micro-LEDs should ideally sustain the high efficiency performances as in traditional LEDs for lighting purposes. ALD sidewall passivation has been shown to gain better optical and electrical performances of Micro-LEDs, and it is important to identify the benefits of ALD sidewall passivation to the overall EQE characteristic. From the literature, the efficiency drop due to sidewall damage and surface recombination has been observed in a range from 10% to 50%, where the deviation can be attributed from several aspects, including epitaxy structure, material quality, or device design[1][2][3]. Similar to the optical and electrical performances, all the 100×100 μm^2 devices resulted in almost identical peak EQE of 40%, regardless of the sidewall passivation techniques. This reinforces that sidewall damage and surface recombination do not have significant impacts to the EQE when sizes are 100 microns or larger, and furthermore other parameters, such as device design that enhances light-extraction efficiency.

In contrast, the external quantum efficiency of III-Nitride Micro-LEDs can decrease drastically in smaller devices, as shown in Fig. 1. For the device without passivation, the efficiency decreased to 15% when reducing the size from 100×100 to 10×10 μm^2. The device with PECVD suffered from lower efficiency than the device without sidewall passivation and yielded distinct trend than other EQE curves. Because the indium tin oxide (ITO) transparency was reduced by the hydrogen radicals from the PECVD chamber, most light was blocked by the less transparent ITO and the performance was worsen in low current density regime. This reveals the use of PECVD sidewall passivation is detrimental to the performances of Micro-LEDs with ITO contact, where ITO is commonly employed as a conductive and transparent *p*-contact due to the resistive *p*-GaN feature. This low transparency ITO issue can be avoided by using metal *p*-contact. Although Micro-LEDs with ALD sidewall passivation did not mitigate the sidewall effect, it showed the peak EQE of 33%, which recovered the peak EQE by more than 30% improvement[4]. The increase in EQE was a consequence of the enhancements in light output power and reduction in leakage current, attributed to the suppression of surface recombination and sidewall damage using ALD sidewall passivation. This work demonstrates that the size-dependent efficiency of Micro-LEDs can be retrieved using proper sidewall treatments to lessen the sidewall effect, yet ALD sidewall passivation alone is unable to eliminate the effects of sidewall damage and surface recombination to maintain size-independent EQE. The work of ALD sidewall passivation serves as the foundation to recover EQE by utilizing post-etch fabrication technique.

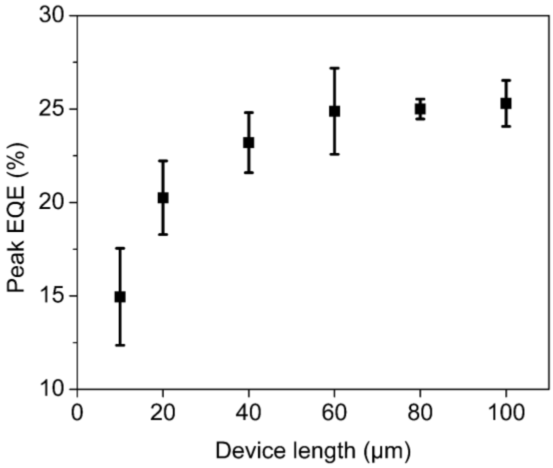

Figure 1. The peak EQE of III-Nitride blue Micro-LEDs drops from 25% to 15% as the size is reduced from 100microns to 10 microns due to surface recombination.

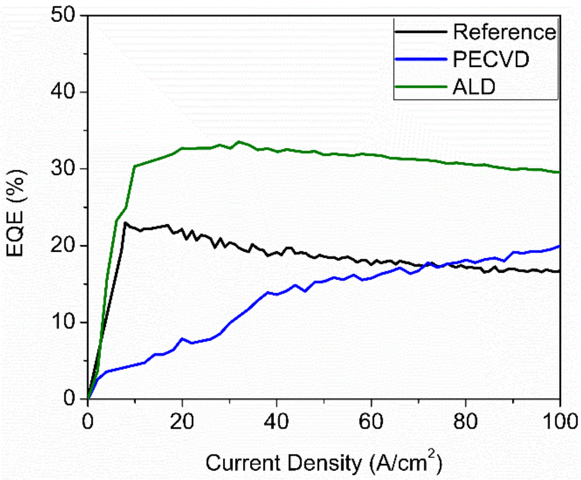

Figure 2. The dependence of EQE on current density of 20×20 μm^2 devices with different sidewall passivation. Reference indicates devices without sidewall passivation, PECVD refers to devices with PECVD sidewall passivation, and ALD represents devices with ALD sidewall passivation. The figure is a modified version of Figure 5b from (Wong et. al[4] for clearer visualization.

The use of MOCVD-grown tunnel junctions for Micro-LEDs is particularly interesting because of their small device sizes, where lateral sidewall activation of the *p*-GaN layer is possible, since the necessary hydrogen lateral diffusion length is anticipated to be shorter in Micro-LEDs than that in other optoelectronic device structures. By utilizing selective area growth in MOCVD-grown tunnel junctions, the *p*-GaN layer has been reactivated and showed no size-dependent voltage penalty, indicating the voltage penalty due to hydrogen passivation can be resolved (Li et al., [5]). Additionally, we estimate that improvements in the light output power and the EQE are more than 10% are possible by replacing ITO with MOCVD-grown tunnel junctions. With further optimizations in doping, junction abruptness, and junction structure, MOCVD-grown tunnel junctions are envisioned to enhance the EQE, by increasing the light extraction efficiency, while providing outstanding electrical characteristics. More importantly, by using MOCVD-grown tunnel junctions in Micro-LEDs, monolithic integration of III-nitride red, green, and blue emitters on the same wafer can be realized.

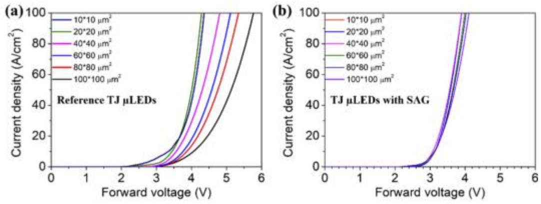

Figure 3. The current density-voltage characteristics of MOCVD-grown Micro-LEDs in various dimensions (a) without selective area growth yielded voltage penalty with different device sizes and (b) with utilizing selective area growth method. Tunnel junction devices with selective area growth obtained size-independent current density-voltage characteristics.

3 CONCLUSIONS

By utilizing advanced semiconductor processing and epitaxial growth we have demonstrated Micro-LEDs with external quantum efficiencies as high as 33% for 20×20 μm^2 devices. Using epitaxially grown tunnel junctions we have further demonstrated low forward voltages of 3.3volts in sizes as small as 10x10microns. Micro-LEDs show much promise as the next generation of energy efficient emissive display technology. This work was supported by the Solid-State Lighting and Energy Electronics Center at UC Santa Barbara.

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