A Bottom-Up InGaN Technology for Ultra-High Brightness R,G,B-Emitting MicroLEDs

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Abstract

We present a bottom-up technology for producing dislocation-free, strain-relaxed InGaN microLEDs in the form of sub-micron scale hexagonal platelets. The use of InGaN barrier material enables high indium-content quantum wells with peak emission tunable from blue to deep red (> 670 nm). These platelets do not suffer from plasma induced damage and exhibit internal quantum efficiency values up to 60% for deep red emitting quantum wells. We further show red microLEDs exhibiting dominant wavelengths above 630 nm for drive currents up to 50 A/cm^2, which is well suited for wide color gamut, and ultra-high brightness displays.

Author Keywords

MicroLED; InGaN; RGB; Sub-micron; CMOS; micro display; color gamut; quantum efficiency; dominant wavelength.

Introduction

MicroLED technology can deliver displays with direct emission of all colors and boasts several advantages over, for instance, OLEDs. Some key benefits of microLEDs over OLEDs are a significantly higher contrast ratio, at least a factor hundred higher brightness, and a factor thousand faster response times. Further, device lifetime is much longer and the range of operating temperatures significantly wider, and more importantly spanning higher temperatures, which is important for *e.g.* automotive displays (1-3).

It is desirable to use the same GaN/InGaN material system to generate red, green, and blue primary colors to simplify LED driver circuitry and to potentially manufacture all three colors on the same epi-wafer. This would simplify mass transfer technology, and bonding to CMOS driver circuitry on Si wafers for full color micro displays.

Planar GaN/InGaN technology can produce high efficiency blue and green LEDs, at least for large pixel sizes. However, for red there are several difficulties. Dominant wavelengths above 630 nm, which is important for wide color gamut displays (in particular for the REC 2020 standard (3-4)), is very difficult to achieve, and even more so at high drive currents (> 10 A/cm^2). This is generally due to the significant lattice mismatch between GaN and the high indium-contents InGaN quantum wells required to push emission beyond 600 nm. The excessive lattice stress for high indium InGaN on GaN is relaxed by creation of dislocation defects that trap charges and results in high non-radiative recombination rates. A large lattice stress also results in a large quantum confined Stark effect which limits the drive current that can be used for deep red emission. The second reason for loss of efficiency is due to plasma processing, needed to shape the mesa defining the pixel size. The plasma processes induce severe damage to the III-nitride materials, leading to much higher surface recombination rates. This becomes more severe as surface-to-volume ratio increases rapidly when shrinking pixel dimensions (5).

There are also significant drives for making GaN/InGaN materials directly on Si wafers to benefit from scaling to 200 mm and beyond. In addition to lowering production cost, this also allows matching of epi-substrate size to Si CMOS driver substrates for applications requiring bonding of LED wafers to CMOS. Producing high-quality GaN/InGaN materials on Si substrates requires rather thick buffer layers to reach high-quality materials. This not only leads to higher epi-costs but potentially also to wafer bow issues which may cause lower integration yields due to wafer breakage in the processing equipment.

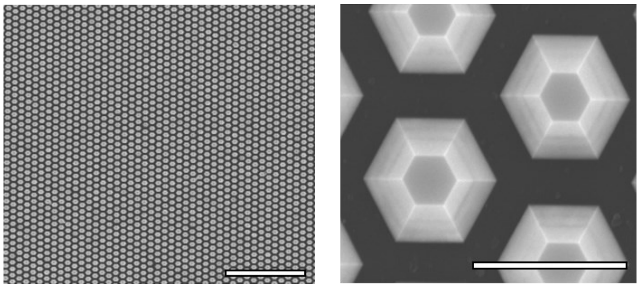

Figure 1 InGaN platelet microLEDs. **Left**. Top view SEM image of platelets. Scalebar is 10 µm. **Right.** Top view showing individual InGaN platelets bounded by six s-plane facets and a top c-plane facet. Scalebar depicts 1 µm.

Here, we present a bottom-up technology that addresses all the abovementioned issues by using sub-micron size, lattice relaxed, dislocation-free InGaN platelets (see Figure 1) on sapphire and Si substrates.

Results

The InGaN platelets were grown using selective area epitaxy in an Aixtron CCS metal organic chemical vapor deposition (MOCVD) system (6-9). Platelets were seeded in 0.1 µm openings in a dielectric growth mask on GaN buffers grown on either sapphire or Si substrates. The GaN buffer typically has a dislocation density of 10^8-10^9 cm^{-2} and can be very thin to enable very low wafer bow substrates. The resulting dislocation free platelets have a truncated pyramidal shape bounded by six sides of crystallographic s-planes and a top c-plane as shown in Figure 1 determined by the slowest growing crystal planes of the hexagonally symmetric InGaN crystal and no plasma processing is needed to define the mesa/platelet. The sidewalls and top c-planes are therefore very smooth, on the atomic scale, and the s-planes have very low growth rates. The platelets have a base diameter of 0.8 µm and a height of 0.5 µm. The platelets are spaced 1 µm apart, however, this may be modified depending on the requirements on sub-pixel spacing.

Each individual platelet contains a full microLED structure and consists (for red LEDs) of a bottom *n*-type $In_{0.15}Ga_{0.85}N$ layer followed by a single $In_{0.36}Ga_{0.64}N$ quantum well (QW) and an $In_{0.10}Ga_{0.90}N$ electron blocking layer sandwiched in between layers

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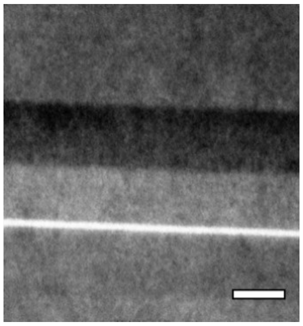

Figure 2 TEM image showing a 3-nm-thick $In_{0.36}Ga_{0.64}N$ quantum well and a 20-nm-thick $In_{0.1}Ga_{0.9}N$ electron blocking layer sandwiched in between $In_{0.15}Ga_{0.85}N$ barrier material. The scalebar is 20 nm.

of $In_{0.15}Ga_{0.85}N$ (see Figure), and finally capped with a top *p*-type $In_{0.15}Ga_{0.85}N$ or GaN layer.

By modifying the composition mainly of the QW, the wavelength of emitted light can be controlled from blue, through green, to red as is shown from the electroluminescence (EL) of platelet microLEDs in Figure 3. In the following sections, only red microLEDs are considered, as they are generally much more difficult to achieve, and blue and green platelet microLEDs typically show better performance than the red.

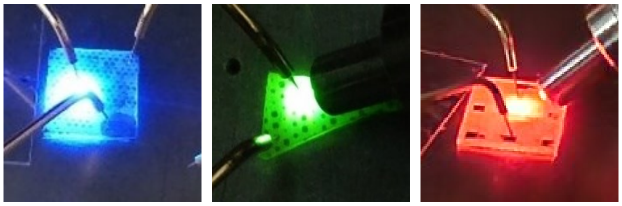

Figure 3 Optical images of electroluminescence from blue, green, and red InGaN platelet microLEDs, showing that indium composition of the quantum well can be adjusted to enable light emission over the entire visible spectrum using the InGaN material system.

To evaluate the material quality, both non-resonant and resonant (to the QW) photoluminescence (PL) was recorded as a function of pumping power and temperature. For resonant measurements a 532 nm laser was used to excite the QW, and temperature was varied from room temperature down to below 10 K. A frequently used method to evaluate the internal quantum efficiency (IQE) is to compare the integrated PL intensity at sub-10 K temperatures where essentially all non-radiative recombination is quenched, to the room temperature PL intensity. Such measurements are shown in Figure 4, where roughly 10 platelets are optically excited and thus contributing to the signal. IQE is seen to increase steadily from 12% up to 59% with increasing laser power. For this sample, peak IQE could not be observed due to too low excitation power available and the 59% IQE value is therefore a lower limit. In other samples with higher background doping, a peak in IQE could be observed for about 10 mW of laser power. Other technologies typically show IQE numbers at, or below 10% for peak emission in the range of 600 – 620 nm. Our technology thus shows at least a factor 6 higher IQE for *sub-1-µm sized structures and at a peak wavelength of 635 nm*. We attribute the high IQE values to very high-quality InGaN material with low residual strain, no dislocations, and low surface recombination velocities.

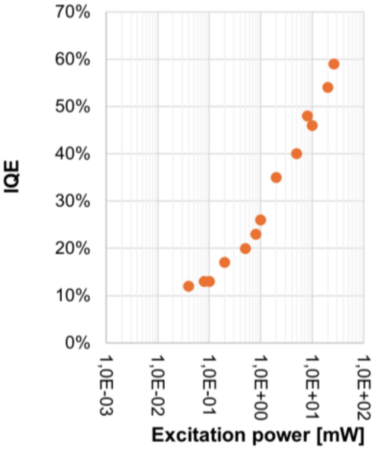

Figure 4 IQE as a function of excitation power of InGaN red microLED platelets having a peak emission wavelength of 635 nm at room temperature.

Next, microLED devices were fabricated using the *n*-type GaN buffer as a common cathode. An Al_2O_3 ALD film was used for surface passivation of the platelet sidewalls, and a planarized (using chemical mechanical polishing) SiN_x layer was used as spacer to place anode contacts to the top *p*-type anodes. Depending on the size of the anode contact, several hundred platelets connected in parallel down to single platelet microLEDs were fabricated. In all measurement data shown here, microLEDs were characterized without any addition of mirrors or other light extraction enhancements.

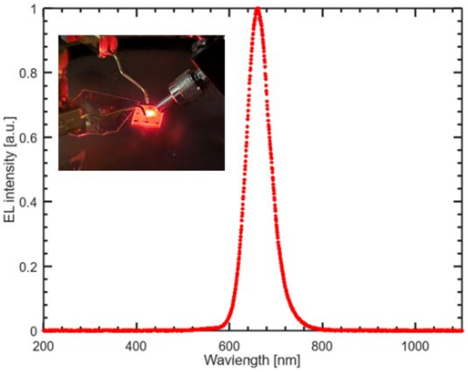

Figure 5 Electroluminescence spectrum from a red InGaN platelet microLED (inset) containing about 50 platelets and driven at 30 A/cm^2 current density. Peak wavelength is 660 nm and FWHM is 57 nm with color purity of 99%.

MicroLED devices of varying sizes, from single platelets to 100's connected in parallel, show very similar characteristics, which is expected if the homogeneities of platelet dimensions, compositions and layer thicknesses are very high. Here we focus on devices containing a few tens of platelets. EL was recorded as a function of current density, ranging from single digit A/cm^2 up to 1000 A/cm^2.

Peak wavelength blueshifts with increasing current density due to quantum confined Stark effects but remains above 630 nm even up to 1000 A/cm^2 current density. As shown in Figure 5, at 30 A/cm^2 peak wavelength is around 660 nm and at very low drive currents the peak is red shifted all the way to 690 nm. Further, the EL peak has full width at half maximum (FWHM) values below 58 nm up to current densities of 200 A/cm^2 and then the FWHM starts to increase. The EL spectrum only shows a single peak, except at very high drive currents (several hundred A/cm^2) when carriers start to recombine also in the $In_{0.15}Ga_{0.85}N$ barrier material and a low intensity peak at 480 nm shows up. This is reflected in the color purity, which falls towards and below 98% at the very highest current densities. Below 100 A/cm^2 color purity is above or close to 99%.

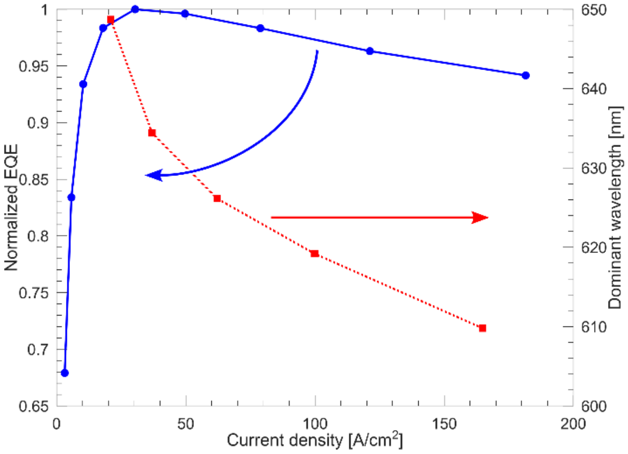

Figure 6 Normalized EQE (blue) and dominant wavelength (red) as a function of current density.

Because the human eye is more sensitive to yellow than to the red part of the visible spectrum, peak wavelength alone does not reflect the color perceived by the eye. Instead, dominant wavelength is a key metric for the red primary color of a display. For wide color gamut displays, the dominant wavelength for red should be 630 nm at the desired operating current of the LEDs. This has turned out to be difficult to achieve, especially at high drive currents (> 10 A/cm^2).

Figure 6 shows both normalized EQE as well as dominant wavelength as a function of current density for a platelet microLED. EQE is here seen to peak at 30 A/cm^2 and then fall off slowly, dropping to 94% of the peak value at 200 A/cm^2. At peak EQE the dominant wavelength is above 640 nm, and it remains above 630 nm up to 50 A/cm^2.

Conclusion and Impact

Here we have presented a bottom-up approach to InGaN microLEDs by growing sub-micron sized truncated InGaN pyramid using conventional selective area epitaxy. Blue, green, as well as red LEDs can be produced in the same InGaN material system, and the structures show IQE values up to 60% for deep red QWs attesting to the high-quality material. Further, the red microLEDs show dominant wavelengths above 630 nm for drive currents up to 50 A/cm^2. These results show that using a bottom-up approach can deliver high-quality material suitable to produce microLEDs for ultra-high brightness displays and may additionally enable full color micro displays based on a single material system.

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