Monolithic integration of tricolor micro-LEDs and color mixing investigation by analog and digital dimming

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Received November 15, 2018; revised November 28, 2018; accepted December 4, 2018; published online April 29, 2019

We report on the growth, processing and optical characterization of monolithically integrated tricolor micro-LEDs. The 100 × 100 μm² active area of the devices is composed of independent subpixels emitting in the blue, green and yellow–orange range with color saturation of over 90% for all bands. The gamut of the device is recorded by both digital and analog dimming, i.e. by pulse width modulation or by varying the current density. Results indicate color mixing performed by both methods leads to a rotated or distorted gamut significantly different from the one predicted by the CIE color model. We explain our findings in terms of quantum-confined Stark effect screening and efficiency droop at high current density, which modify the expected hue and brightness of mixed colors. © 2019 The Japan Society of Applied Physics

1. Introduction

Micro-LEDs (μLEDs) are expected to dominate the future display device market. Organic LED (OLED)-based panels have already been demonstrated to be superior to liquid crystal displays (LCD) in terms of color quality, contrast ratio, response time and energy efficiency.1 However, the recent development and progressive standardization of high dynamic range displays, which require higher brightness levels, have raised concerns about OLEDs’ life spans in spite of the considerable improvements achieved in the last few years.2 Therefore, attention has been focused on AlGaInP- and AlGaInN-based inorganic LEDs, which, respectively, cover the NIR–red–orange and NUV–blue–green ranges of the electromagnetic spectrum. Unfortunately, nitride and phosphate materials do not share the same crystal symmetry, and thus it is necessary to fabricate the chips separately and hybridize them afterwards.3–5 Accurate manipulation of a tremendous number of small subpixels, typically over 10 million for a 4 K resolution, is extremely challenging. In recent years, significant progress has been made in pixel transfer technology, but nitride–phosphate hybridization remains a costly and often imperfect process at the microscale.6 Thus, the monolithic integration of InGaN LEDs as a single material system to cover the entire visible range is highly desirable. Unfortunately, nitrides are extremely inefficient at emitting in the long wavelength range. The main problem concerns the growth of InGaN-based red quantum wells (QWs). Due to the large lattice mismatch between InN and GaN, the InGaN crystal quality deteriorates and the so-called quantum-confined Stark effect (QCSE) increases at high In content. As a result, the quantum efficiency of long wavelength InGaN/GaN QWs is very poor.6,7 Worse, the emission broadens and the perceived color, i.e. the hue of the LEDs, is strongly shifted away from pure red toward orange–amber.8 Therefore, an interesting approach consists of converting the efficient blue light to red light. This can be done by using appropriate phosphors excited by a pump LED matrix, which convert the emission into the desired colors.9 However, phosphors are crystals with typical grain sizes of a few microns. For μLEDs, this means the phosphor coating becomes uneven and leads to significant variation of the color chromaticity over its surface. In addition, phosphors exhibit broad spectral emission, which is suitable for white LEDs with high color rendering index but not ideal for RGB display. Due to their nanoscale size, large bandgap tunability, narrow emission band and high conversion yield, quantum dots (QDs) are promising candidates to replace phosphors in RGB microdisplays.10 QDs can be used to increase the chromaticity of color filters and backlights of LCDs and can also be combined with OLED-based panels in order to improve their color gamut.11 However, QDs are mostly based on toxic CdSe and stable greener alternatives are still under investigation.12 Rare earth elements have also been investigated as color converters. Tm 3+ , Er 3+ and Eu 3+ ions can be introduced in the GaN lattice to provide blue, green and red sharp emission lines.13 Unfortunately, the intensity of such luminescence is rather low since the intra 4f orbital transition is theoretically forbidden by the selection rules. Nevertheless, significant progress was recently reported on Eu 3+ -doped red LEDs exhibiting an external quantum efficiency of over 3% at 20 mA.14

So far, the most promising full nitride-based display has been reported in Refs. 15,16. By controlling the diameter and the pitch of their nanorods (NRs), the authors demonstrated the successful monolithic integration and independent drive of RGBY InGaN/GaN-based LEDs by MBE. In particular, the use of nanostructures helped them to manage and reduce the lattice strain and dislocation density. In addition, the InGaN/GaN QWs are grown on the (10.1) top-facets and present a reduced QCSE. Such an approach led to the improvement of red–orange QWs with internal quantum efficiency of over 15%–20%, while typical values for planar polar QWs saturate at around 5%.17 However, the approach partially relies on the shadowing effect of the surrounding rods and one may question the color homogeneity of the pixels (for instance on their borders) and the capabilities for
transferring such a technique to very small pixels (few identical neighbors and limited or parasitic shadowing from different neighbors). More generally, metal organic vapor phase epitaxy (MOVPE) is more suitable for LED production. Unlike MBE, which is a ballistic process performed under high vacuum, MOVPE is a chemical process involving a vapor phase. Therefore, the MOVPE growth of QWs on NRs commonly leads to core–shell structures displaying different QW compositions and thicknesses depending on their facet orientations. Such NR-based LEDs present multifacet emissions from red to blue, but the strong dependence of the colors on the driving current is unsuitable for RGB display applications. In order to achieve independent subpixels, tandem LEDs are interesting structures that have already been applied to bicolor LEDs. Following a similar approach, we demonstrate the successful growth and monolithic integration of tricolor μLEDs displaying high color saturation. Subpixels are driven independently and the gamut of the device is investigated using both analog and digital dimming modes. We analyze the brightness, the hue and the saturation of the pixel and correlate the resulting color properties to the QCSE and efficiency droop of the μLEDs.

2. Growth of the tricolor structure

The structure consists of three LEDs (blue, green and yellow/orange) directly stacked on top of each other on both GaN/sapphire templates and GaN bulk wafers, and grown without interruption in an EpiQuest showerhead MOVPE reactor. Each LED substructure is made of 500 nm n-GaN, three InGaN/GaN QWs and a 250-nm-thick p-GaN (except for the last p-GaN, whose thickness is only 125 nm). The growth of InGaN/GaN QWs and a 250-nm-thick p-GaN (except for the last p-GaN, whose thickness is only 125 nm). The growth of the QWs was carried out under a H2/N2 gaseous mixture, at a pressure of 200 Torr with an In/Ga ratio of 0.93 using ammonia (NH3), triethyl-gallium and trimethyl-Indium as precursors. Three pairs of InGaNs0.20Ga0.80N QWs were grown at 770, 740 and 720 °C, resulting in In composition of 15, 20 and 23%, respectively. Each well was capped by a 1-mm-thick GaN layer before ramping up the temperature and growing the barrier at 900 °C. The QWs were calibrated by X-ray diffraction prior to the growth. For the p- and n-GaN layers, bisethylcyclopentadienyl-magnesium, tetramethyl-silane, trimethyl-gallium and NH3 were used as precursors and both layers were grown under similar conditions, namely under pure H2, at a pressure of 150 Torr and at a moderate temperature of 975 °C to prevent thermal decomposition of the QWs. The IV/III and II/III ratios were set to 2.7 × 10−3 and 3.7 × 10−2, respectively. The growth rate and V/III ratio were about 10 nm min−1 and 7200, respectively, in order to ensure sufficient mobility of the Ga adatoms and limit the carbon incorporation. Figure 1 presents the cross-section of the as-grown structure measured by scanning electron microscopy (SEM) and its secondary ion mass spectroscopy (SIMS) profile analysis.

The SIMS profile shows that the Si and Mg doping levels are about 1 × 1019 and 6 × 1019 cm−3, respectively. These values are in good agreement with the electron and hole concentrations that were estimated at around 1 × 1019 and 2 × 1017 cm−3, respectively, by Hall effect measurements prior to the growth. While the Si profile is abrupt, the Mg signal shows a strong memory effect with doping tails extending into the top layers. The Mg concentration decreases of one decade after 55 nm, and two decades after 230 nm, of n-GaN overgrowth are consistent with previous reports. Interestingly, the sharp H profile indicates that H is not significantly incorporated into the Mg tail of the n-GaN due to the pinning of the Fermi level near the conduction band (note that, in contrast, it fully passivates the Mg in the p-GaN as the Mg/H ratio is close to one). This means that the Mg present in the n-GaN is fully activated. Nevertheless, only a small percentage of the Mg dopant is ionized at room temperature. Therefore, the Mg level remains lower than that of the Si and the conductivity of the n-GaN top layers is not significantly affected. The carbon and oxygen levels are roughly constant throughout the growth with concentrations about 1017 and 1016 at cm−3, respectively.

3. Processing of the device

The structure grown on GaN substrate was processed in arrays of 5 × 5 tricolor pixels by standard photolithography using Ni and photoresist masks. Independent subpixels were first separated with 3.5-μm-deep trenches by inductively coupled plasma reactive ion etching (ICP-RIE) using Cl2 [Fig. 2 (a)]. The blue and green LEDs were selectively exposed by further etching the sample down to the middle of their p-GaN layers [symbol + in Figs. 2(b) and 2(c)]. Then, blue, green and yellow mesas with respective 35 × 35, 35 × 50 and 50 × 100 μm2 surface areas were simultaneously defined by etching once more the structure down to the middle of the n-GaN layers [symbol – in Fig. 2(d)]. Then, the sample was annealed in an oven at 700 °C in N2 ambient for 10 min in order to activate the p-GaN. Afterwards, N5nm/Au100nm electrodes were deposited by e-beam on the p-GaN and annealed for 10 min in air at 500 °C [Fig. 2(e)]. The overall surface of the device was then insulated with a 600-nm-thick SiO2 layer deposited by plasma-enhanced chemical vapor deposition, and windows directly above the electrodes were opened in the dielectric layer by RIE using CF4 [Fig. 2(e)]. The device was finally completed by connecting the mesas with 5-μm-wide gold channels terminated with 70 × 100 μm2 pads. In summary, each pixel is a 300 × 300 μm2 box divided into three subpixels having their own negative and positive terminals [respectively, symbols G and +V in Fig. 2(h)]. The tricolor active area is located at the center of the pixel and totals 100 × 100 μm2 in surface.

4. Color mixing investigation

Optical measurements were carried out at room temperature. A four-probe station connected to a 4155 C Agilent was used to characterize the μLEDs individually or in pairs. The emitted light was collected from the bottom, using either an Ocean Optics fiber multi-channel spectrometer or a simple planar Si photodetector. The integration time varied from milliseconds to seconds depending on the dimming mode used to evaluate the gamut of the device.

Electroluminescence (EL) measurements were first carried out on single μLEDs [Fig. 3 (left)]. At a current density of about 100 mA cm−2, the μLEDs emit at 497, 555 and 583 nm, allowing the pixel to cover a large range of colors from blue—green to yellow—orange. Color saturation for
each band is higher than 90%, even for the broad yellow emission, as expected for InGaN/GaN-based LEDs. At higher current density, the screening of the QCSE shifts the QW emissions toward shorter wavelengths. At about 1 A cm$^{-2}$, the EL peak wavelength of the LEDs is moved to 494, 542 and 558 nm, corresponding to a blue-shift of 3, 13 and 25 nm, respectively. It is well known that QWs emitting at longer wavelengths display a stronger

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**Fig. 1.** (Color online) SEM cross-section of the as-grown structure showing the different n-GaN and p-GaN layers. The position of the QWs is highlighted by colored arrows. On the right, the SIMS profile indicates the Si, Mg and H concentration in the different layers.

**Fig. 2.** (Color online) SEM and laser microscopy pictures of the device at the different processing steps. The subpixels are first electrically separated by deep trench etching (a) and the green and blue subpixels are exposed by ICP-RIE (b and c). Mesas are simultaneously fabricated by plasma etching (d) and the electrodes deposited by e-beam evaporation (e and f). The overall surface of the device is insulated by SiO$_2$, windows are opened directly above the electrodes (g) and the mesas are connected by gold channels (h). The pixels are organized in 5 $\times$ 5 arrays (i). The scale bar in pictures (a) to (g) represents 100 $\mu$m.
piezoelectric field and suffer of larger wavelength shift at high current density.\textsuperscript{7,28)} From a multi-color device perspective, it means that cool colors are relatively stable while warm colors are prone to significant hue shift upon driving current.

In order to study the pixel colors, the subpixels’ emissions were mixed two by two (Fig. 3 right). Because the blue, green and yellow \( \mu \)LEDs had different efficiencies, the current density in each \( \mu \)LED was freely tuned between 0.1 and 1 A cm\(^{-2}\) in order to obtain comparable EL intensities as necessary for the analysis. Controlling the optical power (OP) of an LED by tuning either its current or its voltage is referred to as analog dimming. However, this approach results in several problems. Firstly, the driving current of nitride-based LEDs is not proportional to their OP, mostly due to the so-called efficiency droop.\textsuperscript{29)} In other words, varying the current (or the voltage) of an LED does not allow linear control of its luminosity. Secondly, and most importantly, the emission wavelength, i.e. the hue of the LED, undergoes a significant shift at high current density as previously discussed. This is particularly visible in Fig. 3 (right) where the EL spectra, mainly dominated by the \( \mu \)LEDs driven at high current density, are clearly blue-shifted in respect to their original position. To overcome such detrimental effects, LEDs are commonly dimmed by pulse width modulation (PWM), also referred to as digital dimming. The LEDs are switched on and off at a frequency \( f \) (typically above 100 Hz to avoid flickering) and the average OP is linearly controlled by tuning the pulse width, i.e. the duty cycle of the pulse train. By doing so, the hue of the emission remains unaffected and, interestingly, the LED can be driven at its maximum internal quantum efficiency current. As an example, the characteristics of \( \mu \)LED\( _3 \) driven by both analog and digital dimming are summarized in Fig. 4.

We calculated the CIE \( xy \) chromaticity coordinates of the EL spectra recorded by both analog and digital dimming.\textsuperscript{30)} Figure 5 (left) shows the results obtained by mixing the three LEDs two by two using PWM at duty cycles of 0, 20, 40, 60, 80 and 100%. In agreement with the theory, the coordinates of the mixed color fall on segments connecting the coordinates of the pure colors. The segments define the gamut of the pixel, i.e. the complete range of colors that can be achieved by all possible combinations of the subpixels. Interestingly, the gamut rotates counterclockwise when the current density increases from 0.1 to 1 A cm\(^{-2}\) (dash and solid lines, respectively). This phenomenon originates from the screening of the QCSE: while the EL peak wavelength of each LED is blue-shifted, the coordinates of the corners of the gamut move counterclockwise along the spectral locus of the chromaticity diagram. Figure 5 (right) shows another disadvantage of analog dimming. The mixed color coordinates are not properly aligned on a triangle (white stars, solid line—calculated from the EL spectra of Fig. 3). Indeed, since the dimming is performed by increasing the current density in one LED while decreasing it in the other, both ends of the segments move in opposite directions. This creates curves in the sides of the gamut, whose corners are defined by the colors of the LEDs driven at 1 A cm\(^{-2}\). Therefore, not only the luminosity but also the hue of mixed colors are not easily controlled by analog dimming.

It is worth pointing out that nitride-based LED manufacturers certify the emission peak wavelength as well as the dominant wavelength of their products at a specific operating current. Indeed, even if attention is usually paid to mitigate the QCSE, a slight hue shift can still occur over a large range of driving currents. Due to their larger piezoelectric field, yellow-orange-red InGaN-based LEDs are particularly prone to such color variation.\textsuperscript{7,31)} Interestingly, the color correlated temperature (CCT) of white LEDs is also affected when varying their driving current. In this case, it is the efficiency of the phosphor conversion which decreases at higher current density and causes the CCT to drift toward cooler hues.\textsuperscript{32,33)} In summary, whatever the application, PWM is recommended for dimming nitride-based LEDs.
5. Conclusion

Tricolor $\mu$LEDs were successfully grown and monolithically integrated by a simple photolithography process. The subpixels of the device were driven independently and their EL spectra covered a broad spectral range, from blue–green to yellow–orange. The gamut of the device was recorded by both analog and digital dimming. Although analysis by PWM led to a perfectly triangular gamut as predicted by theory, increasing the current density rotated the gamut counterclockwise. In addition, analog dimming of the subpixel led to a more complex distorted gamut. These findings were explained in terms of QCSE screening inherent to nitride LEDs driven at high current density. Upgrading such a tricolor device following the recent progress made on tunnel junction $\mu$LEDs\(^3\)--\(^6\) and InGaN/AlGaN-based red LEDs\(^7\) could enable the fabrication of full nitride RGB microdisplays.

Acknowledgments

Y. R. would like to thank R. Chevallier for fruitful discussion on device processing. This work was supported by Aichi Science and Technology Foundation Knowledge Hub Aichi Priority Research Project E and by JST (Japan Science and Technology Agency), Strategic International Collaborative Research Program, SICORP.

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