Two-dimensional multicolor (RGBY) integrated nanocolumn micro-LEDs as a fundamental technology of micro-LED display

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The development of high-productivity microLED (μ-LED) pixel panels is crucial as a key technology for next-generation displays. To provide a fundamental approach to this end, in this study, multicolor (red, green, blue, and yellow; RGBY) nanocolumn (NC) μ-LED pixels with 5 × 5 μm² emission windows were monolithically integrated to exhibit electroluminescence spectra with peak wavelengths of 478, 512, 559, and 647 nm, respectively. The NC μ-LED pixels, which were two-dimensionally arranged with a 10 μm period, were individually driven by the matrix wiring p- and n-electrodes, exhibiting a μ-LED pixel panel arrangement. © 2019 The Japan Society of Applied Physics

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Micro-LEDs (μ-LEDs)†1–5 have attracted considerable attention as a disruptive technology for displays,5 because they inherently provide high brightness, high contrast ratio, high response speed, long lifetime, and power saving, and can be operated over a wide temperature range.6–8 Therefore, the development of μ-LED displays is crucial for applications to augmented reality, virtual reality, wearable watches, mobile phones, micro projection displays, and so on. Indium gallium nitride/gallium nitride (InGaN/GaN) LEDs play an important role in μ-LED displays. However, it is difficult to fabricate high-efficiency InGaN-based red-emitting LEDs, because of the lower radiative recombination rate as well as the worsening crystal quality as the In content increases.7,9 GaN nanocrystals (NCs)10–12 are columnar nanocrystals that exhibit excellent properties such as dislocation-free13,14) lattice strain relaxation15,16) and no generation of misfit dislocations at the InGaN/GaN hetero-interfaces.16) These nanocrystal effects12) contribute to the improvement of emission efficiency of the InGaN-based visible LEDs from green to red. For the green (535.5 nm) LED, the product of the internal quantum efficiency (IQE) and current injection efficiency was reported to be 44% at ~60 A cm⁻² (see Fig. 10 in Ref. 17) and the IQE at 600 nm was evaluated to be 22%.18) Furthermore, the position and diameter (D) of the GaN NCs were precisely controlled by the developed Ti-mask selective area growth (SAG) of GaN19–22) to fabricate InGaN/GaN NC ordered triangle-lattice arrays with the lattice constant (L).17,22–24) It was found that the emission color for such ordered arrays with the InGaN/GaN multiple quantum well (MQW) changed from blue to red with an increase in D,24) the color change mechanism was explained by the beam shadowing effect and the difference in the diffusion length between the In and Ga adatoms on the NC sidewall.23) Based on the experimental finding, the monolithic integration of InGaN-based NC LEDs with different emission colors (blue, green, yellow, and red) was demonstrated.25,26) The LEDs in the device had emission windows of 65 μm, i.e. size of the μ-LED, which were arranged in the distance of 190 μm. These characteristics of the NCs show that they can be used as a fundamental platform for the development of μ-LED displays. In this study, therefore, InGaN/GaN NC ordered arrays were investigated to provide a fundamental technology for μ-LED displays.

In μ-LED displays, μ-LED pixel units comprising three primary colors (red, green, blue; RGB) are two-dimensionally (2D) arranged and individually addressable using Si- complementary metal-oxide semiconductor (CMOS) active-matrix integrated circuits (ICs).3,4) In general, RGB μ-LED chips, which are individually fabricated from RGB film-LED crystals through a top-down etching,27) are arranged on the driver IC wafer through the pick and place process. This process is time-consuming, and it is difficult to achieve high-precision position control of ultramicroscopic LED pixels of 5–10 μm square area. Furthermore, the etching damage at the sidewalk of the miniaturized LED chips causes a decrease in the emission efficiency through the increased surface recombination. For this technology, GaInNp-based red LEDs are utilized. The crystal surface of (Al)GaInN, however, is irritably affected by the damage, thereby resulting in serious deterioration of the efficiency of red μ-LEDs. To overcome this problem, wet etching of the damaged layer and the subsequent surface passivation is effective,27) but these techniques are still under development for red. At the same time, color-conversion materials such as phosphor28) and quantum dots (QDs)29–30) are utilized along with the excitation sources of UV28,29) or blue μ-LED arrays.30) The large size of the phosphor particles (4–22 μm)28) limit the downsizing of μ-LEDs. For the QD-based μ-LEDs, the QD layers are unable to achieve complete absorption of the underneath LED light. Thus, distributed Bragg reflectors are utilized to increase the color-conversion efficiency,29,30) complexing the device structure. The RGB color-conversions by a UV LED excitation experience Stokes shift loss, decreasing the efficiency. Therefore, additional research is required to identify an effective technology for μ-LED displays.

Given these circumstances, the monolithic integration of InGaN-based RGB μ-LEDs, which is attained using the NC platform, is an important approach for the development of μ-LED displays. The monolithic integration by the NCs

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enables the downsizing of the RGB LED pixel unit to a small area, such as $10 \times 10 \mu m^2$ or less. Using this technology, multicolor InGaN-based NC LEDs were monolithically prepared in a one-step SAG\textsuperscript{25,26,31}) where patterned substrates controlled the NC parameters to change the In content of the InGaN active layers grown on top of the GaN NCs, thus producing visible emissions from blue to red. For InGaN/GaN NCs, the core–shell\textsuperscript{16,32}) or QD InGaN structures\textsuperscript{31,33}) are self-assembled. Therefore, the carriers are confined to the centers of the NCs, and the surface recombination at the sidewall is suppressed.\textsuperscript{32}) The NC $\mu$-LEDs investigated here are essentially freed from the etching damage, which results in serious deterioration in efficiency for the top-down etched $\mu$-LED chips.

Accordingly, we fabricated a 2D ($16 \times 16$) arrayed InGaN/GaN-based NC $\mu$-LEDs with different emission colors, as schematically shown in Fig. 1(a), where the NC LEDs were prepared through the fundamental fabrication process\textsuperscript{12,17}) (see the supplementary material, which is available online at stacks.iop.org/APEX/13/014003/mmedia); Fig. 1(b) shows a top-view photograph of the device. In the fabrication, $10 \times 10 \mu m^2$ sized triangle-lattice ordered arrays of InGaN/GaN-based pn-junction NCs with the thick InGaN active layers were 2D grown in $40 \times 40$ square over a $400 \times 400 \mu m^2$ area using a Ti-mask SAG\textsuperscript{19–21}) and the matrix wiring electrode was prepared on the $16 \times 16$ pixel array (see Fig. 1(b) and supplementary material). The ordered arrays functioning as NC $\mu$-LED pixels were grouped individually into multicolor integration units [see Fig. 1(c)], which were composed of four types of ordered arrays, namely pixels $a–d$, with $L = 100$, 150, 250, and 350 nm, respectively. For pixels $a–d$, the ordered NC arrays were controlled to achieve high filling factor (FF) values of 60%–75% and the values of $D$ at the active layers were 85, 130, 196, and 282 nm. Here, the thickness of InGaN was approximately 70 nm for $L = 350$ nm.

Figure 1(c) show a top-view scanning electron microscope (SEM) image of one multicolor integrated NC $\mu$-LED unit consisting of four pixels ($a$, $b$, $c$, and $d$) with the blue, green, yellow, and red emission colors, respectively. NC $\mu$-LED pixels with $5 \mu m$ square transparent electrodes arranged in a square lattice with a $10 \mu m$ period. (b) and (c) are different samples, but a red square in (b) indicates the corresponding place in (b) of the integration unit of (c).

![Figure 1](image_url)

*Fig. 1.* (Color online) (a) Schematic diagram of a 2D arranged device of multicolor NC $\mu$-LEDs. (b) Top-view photograph of 2D ($16 \times 16$) arrayed NC $\mu$-LEDs with different emission colors with matrix wiring electrodes; each LED was individually addressable in current injection by a matrix wiring for $p$- and $n$-electrodes. (c) Magnified image of one multicolor integrated NC $\mu$-LED unit, consisting of pixels $a$, $b$, $c$, and $d$ with the blue, green, yellow, and red emission colors, respectively. NC $\mu$-LED pixels with $5 \mu m$ square transparent electrodes arranged in a square lattice with a $10 \mu m$ period. (b) and (c) are different samples, but a red square in (b) indicates the corresponding place in (b) of the integration unit of (c).
A function of NC diameter in the underlying n-GaN region. 

resistance and restrict the downsizing of the pixel area. To overcome this problem, flip-chip bonding on the Si CMOS driver IC substrate, followed by laser lift-off for the sapphire substrate, is more appropriate for the production of μ-LED displays. In addition to that, note that the growth of NC LEDs on Si substrates will be suitable for the flip-chip bonding. However, this experiment provides a fundamental demonstration of RGBY-integrated NC μ-LED pixels.

The emission properties of the integrated NC μ-LED pixels with thick active layers were evaluated under a direct current injection at room temperature, detecting the electroluminescence (EL) signals by a microscope with a 40× objective lens (NA = 0.6) combined with a monochromator; the emission images were observed by a charge-coupled device camera. Figure 2(a) shows the emission images of one integration pixel unit. Blue, green, yellow, and red emissions were observed for pixels a, b, c, and d, exhibiting normalized EL spectra with peak wavelengths at 478, 512, 559, and 647 nm, respectively [see Fig. 2(b)], where the device were evaluated on the wafer level probing on the electrode pads. This experiment showed that the RGBY NC μ-LEDs can be monolithically integrated in a micro-sized area of 20 × 20 μm². As can be seen by Fig. 2(b), however it is necessary to improve the emission spectral purity for the display application, which could be achieved by the controlled growth condition of InGaN and then the NC photonic crystal contributes to narrowing the spectral linewidth. And the peak wavelengths should be more precisely controlled to RGB. A monotonic increase in the EL peak wavelength (from 478 to 647 nm) was observed as D increased as shown in Fig. 2(c). For densely-packed InGaN/GaN NC arrays with FF ∼ 80%, the photoluminescence peak wavelength was reported to be changed from blue 460 nm to red 630 nm with increasing D. The wavelength change, however could not be explained by only the beam shadowing effect owing to the continuously high FF of the NCs employed in this experiment. At the moment, the compositional change mechanism for thick InGaN active layers is still not completely understood, although it could be explained by In-cohesion at the NC center that produces the core–shell InGaN (see supplementary material). The systematic consideration will be discussed elsewhere.

Figure 3(a) shows the SEM image of the 2D NC μ-LED pixels; LED pixels with a 5 × 5 μm² injection area were arranged in the 10 μm period. The emission image of one green pixel at 500 μA captured via a smartphone is shown in Fig. 3(b); the green emission light was confined within the crystal owing to total reflection at the surface, thus spreading into the neighboring μ-LED pixels and the underlying sapphire substrate. The small light extraction efficiency restricted the light output to the front side of the current device, but a spread green emission was brightly observed in a lighted room [see Fig. 3(b)]. In the application to μ-LED pixel panels, we should devise the light to be extracted preferentially on the front side of the pixel panel. For this purpose, the introduction of an optical isolation scheme between the neighboring pixels is effective, where the laterally traveling beams at each pixel boundaries are reflected, which also avoids color mixing. The deposition of metal on the pixel side through the underlying insulating film might be a simple method for this. The use of the photonic crystal effect also enhances light extraction. When the flip-chip bonding of full-color pixel arrays on the Si CMOS driver IC substrate is performed, the metal or dielectric multilayer reflector on each driver cell will increase the light extraction to the front side. The development of transparent transistors would more simplify the framework of display.

The injection current versus applied voltage (I–V) and light output versus injection current (L–I) characteristics are...
shown in Figs. 4(a) and 4(b), respectively. Clear rectifier diode characteristics were observed for all pixels, with similar turn-on voltages of ~2.5 V for all pixels. The backward current was evaluated here to be $10^{-9}$ A at the reverse bias voltage of 3 V for pixels $a$ and $b$; however, it was $10^{-6}$ and $10^{-7}$ A for pixels $c$ and $d$, respectively. The $L$–$I$ characteristics for the current range of 0–500 $\mu$A (current density of 2 kA cm$^{-2}$) are shown in the figure although the device was driven up to the injection current of 1 mA (current density of 4 kA cm$^{-2}$; see Fig. 2). The light intensities of blue to red LED pixels are different from the ordinarily expected order for blue to red internal quantum efficiencies; the maximization of the intensity at the yellow emission could be specific to the fabricated device. For pixels $a$ and $b$, the light output increased linearly with an increase in the injection current, while for pixels $c$ and $d$, nonlinearities in the $L$–$I$ characteristics were observed in the low injection current range, which mostly likely indicates the presence of the current leakage component, as discussed in a previous study.\textsuperscript{17} At the same time, a low efficiency droop is required for display application of the $\mu$-LED panel. For the green NC LED, the efficiency was maximized at ~60 A cm$^{-2}$, and an efficiency droop of 21% was observed at 450 A cm$^{-2}$.\textsuperscript{17} which was smaller than that of the green InGaN film-MQW LEDs, whose droop was 54%.\textsuperscript{15}

Figure 5(a) shows the total EL spectra of an integrated NC $\mu$-LED unit when four $\mu$-LED pixels (a–d) were driven alternately by the pulse current of 500 $\mu$A, using even and enhanced pulse durations ($T_i$; $i=a, b, c, d$). For the pulse measurement, the device was wire-bonded on a chip package, as shown in Fig. 1(b). This experiment was performed for a device different from that mentioned above; the peak wavelengths of pixels $a$, $b$, $c$, and $d$ were 497, 506, 540, and 610 nm, respectively. When pixels a–d were driven by an even pulse duration of $T_a = T_b = T_c = T_d = 1$ ms, the total light intensity monotonically decreased from blue to red, showing a decrease in the efficiency of InGaN. To enhance the intensity in the green and red range, the pulse durations of pixels $a$–d were changed to be $T_a = T_b = 1$ ms, $T_c = 8$ ms, and $T_d = 35$ ms. A broad emission spectrum with enhancement in the red range [the red curve appears in Fig. 5(a)] was observed. This experiment indicates that an improvement in the efficiency of the red $\mu$-LED poses a challenge for $\mu$-LED displays, though a simple technique in handling that is to integrate two red $\mu$-LEDs for each full-color pixel.

The well-controlled NCs presumably contribute to addressing this issue. For the InGaN/GaN NCs, the self-assembled InGaN core–shell structure described above suppresses the surface recombination of carriers. Under this condition, the nanocrystal effects of NCs, such as strain relaxation, suppressed misfit dislocation, and dislocation filtering effects, are advantageous for improving the emission efficiency of the red InGaN. An IQE of 22% was reported for 600 nm InGaN/GaN NCs.\textsuperscript{18} Recently, PL intensity enhancement at 600 nm via surface plasmon and exciton coupling was reported as a technology for improving the IQE.\textsuperscript{42} Note that the plasmonic metals should be placed at distances less than several tens of nm from InGaN.\textsuperscript{43} Reducing the thickness of the p-cladding layer for InGaN film LEDs poses a challenge to high-performance operation. However, the plasmonic effect is effectively introduced in NC LEDs, because plasmonic metals (Au or Ag)\textsuperscript{42,43} are deposited on the sidewall of the NC LEDs, close to the InGaN active layer, and do not conflict with the current injection scheme. Therefore, it is expected that the selective deposition of plasmonic metals on red NC LED pixels will contribute to improving the efficiency.

In summary, the monolithic integration of NC $\mu$-LED pixels with $5 \times 5 \mu$m$^2$ ITO electrodes arranged with the 10 $\mu$m period was demonstrated for creating multicolor integration $\mu$-LED pixel units. The integration units were 2D arranged in an 8 $\times$ 8 square lattice, and individual $\mu$-LED pixels were independently driven using the prepared matrix wiring electrode system. For one multicolor integration unit, the blue, green, yellow, and red emissions were observed to exhibit EL spectra with peak wavelengths at 478, 512, 559, and 647 nm, respectively. Thus, the experiment provided the fundamental demonstration of a NC $\mu$-LED pixel panel arrangement.

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