Demonstration of 621-nm-wavelength InGaN-based single-quantum-well LEDs with an external quantum efficiency of 4.3% at 10.1 A/cm²

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ABSTRACT

Here, we report highly efficient InGaN-based red light-emitting diodes (LEDs) grown on conventional c-plane-patterned sapphire substrates. An InGaN single quantum well active layer provides the red spectral emission. The 621-nm-wavelength LEDs exhibited high-purity emission with a narrow full-width at half-maximum of 51 nm. The packaged LED’s external quantum efficiency, light-output power, and forward voltage with a 621 nm peak emission wavelength at 20 mA (10.1 A/cm²) injection current were 4.3%, 1.7 mW, and 2.96 V, respectively. This design development represents a valuable contribution to the next generation of micro-LED displays.

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InGaN is an excellent candidate material for light-emitting devices in the visible spectral range. It is available to turn the bandgap in the material composition adjustment. The red, green, and blue (RGB) full-color micro-light-emitting diodes (LEDs) for next-generation displays are currently of considerable interest. InGaN-based blue and green LEDs have maximum external quantum efficiencies (EQEs) that exceed 80% and 50%, respectively. Those LEDs fulfill the feasible technology even through micro-LED fabrication. The red LEDs based on AlGaNnP achieve a high EQE of over 60%. However, these LEDS become considerably less efficient as the dimensions of the device shrink. The efficiency of LEDs is limited by the physical parameters of its material components, such as high surface recombination and long carrier lifetime. This suggests that nitride-based red micro-LEDs possess higher efficiency potential than those based on AlGaNnP. Therefore, efforts toward developing red LEDs based on nitride materials have expanded. However, the efficiency of InGaN-based red LEDs significantly reduces as the In-content in the active region increases. The low efficiency of the InGaN-based red LEDs represents a bottleneck in developing full InGaN-based RGB LEDs. The major challenge in realizing highly efficient InGaN-based red LEDs is overcoming the fundamental issues of the materials—the major issues hindering epitaxial growth present as low-temperature growth and large mismatches.

Furthermore, high-In-content InGaN-based LEDs are susceptible to the strong quantum-confined Stark effect (QCSE) in the InGaN active regions. These issues with the optical properties manifest as large peak wavelength shifts and reduced internal quantum efficiencies (IQEs).

Several approaches have been proposed to mitigate the lattice mismatch between InGaN active regions and their underlying layers. These presume that the crystalline quality of the InGaN active region can be improved because the growth temperature increases due to In pulling effect. InGaN-based red LEDs can grow on pseudo-substrates (e.g., InGaNOS substrate and InGaN on porous GaN). Such LED devices have a large redshifted peak emission wavelength compared with those grown on standard GaN templates. Even LEDs
grown on GaN/Si substrates display an enhanced In incorporation rate into InGaN QWs due to the introduction of tensile strain from the underlying GaN layer.\(^{22,23}\) Recently, 608-nm-wavelength InGaN LEDs have demonstrated as high as a peak wall-plug efficiency (WPE) of 23.5% at 0.8 A/cm\(^2\).\(^{23}\) The increment of the InGaN growth temperature is a key factor in enhancing the performance of a device. Meanwhile, the structural design of the active region is also essential for developing highly efficient InGaN-based LEDs. Previously, we reported several approaches toward reducing defect generation in InGaN QWs, such as strain compensating barrier layers, hybrid QW structures, and thick GaN templates.\(^{24–26}\) Those efforts have contributed to the device performance of InGaN-based red LEDs. However, the EQEs of even the state-of-the-art InGaN-based red LEDs are so far from that of typical blue and green LEDs.\(^{16,18,21,26}\) Due to its high-In-content, the InGaN active layer for red emission has fundamental issues, including a large QCSE and poor material quality.

This work describes InGaN-based red single-quantum-well (SQW) LEDs with an emission peak wavelength of over 621 nm. The LEDs have a light-output power of 1.7 mW at 20 mA of injection current for an EQE of 4.3%. The details of the optoelectrical properties are discussed.

InGaN-based LED structures were grown on conventional c-plane-patterned sapphire substrates using a metalorganic vapor phase epitaxy (MOVPE) in a single-wafer horizontal reactor.\(^{27,28}\) Figure 1(a) shows a schematic of the cross-sectional structure of InGaN-based red LEDs. We used c-plane sapphire substrates with a cone-shaped morphology that were 1.6 \(\mu\)m in height, 2.6 \(\mu\)m in diameter, and spaced every 0.4 \(\mu\)m. The InGaN-based LED structure consisted of a 2 \(\mu\)m-thick, unintentionally doped (uid) GaN layer with a low-temperature GaN buffer layer, an 8 \(\mu\)m-thick Si-doped n-GaN layer, a 1 \(\mu\)m-thick Si-doped n-Al\(_{0.03}\)Ga\(_{0.97}\)N contact layer, 30 periods of a uid-superlattices (SLs) structure with 6-nm-thick GaN and 2.5-nm-thick In\(_{0.08}\)Ga\(_{0.92}\)N layers, a 15-nm-thick Si-doped n-GaN layer, a 2.5-nm-thick InGaN blue SQW, 5-nm-thick uid-GaN/18-nm-thick Si-doped n-Al\(_{0.13}\)Ga\(_{0.87}\)N/11-nm-thick uid-In\(_{0.02}\)Ga\(_{0.98}\)N barrier layers, a 3.5-nm-thick InGaN red SQW as the active layer, 1-nm-thick uid-AlN/30-nm-thick uid-GaN barrier layers, a 22-nm-thick Mg-doped p-Al\(_{0.1}\)Ga\(_{0.9}\)N electron blocking layer, a 90-nm-thick Mg-doped p-GaN layer, and a 10-nm-thick heavily Mg-doped p\('\)GaN contact layer. The thick underlying n-GaN layer, with the reduction of in-plane stresses, can improve the crystal quality of the InGaN active region.\(^{26}\) Note that the n-AlGaN contact layer contributes to its smooth surface morphology despite its high Si-doping concentration (\(>10^{19}\) cm\(^{-3}\)) and obtains a lower series resistance.\(^{29}\) Figures 1(b)–1(e) present the cross-sectional high-angle annular dark-field (HAADF)-scanning transmission electron microscopy (STEM) and the energy-dispersive x-ray spectroscopy (EDS) mapping images of the InGaN-based LEDs. This confirmed the compositional uniformity of the materials presented for each epitaxial layer by these elemental mappings. We adopted several growth techniques to improve the material quality in the active region. Interestingly, the active layer for the red emission used the SQW structure. According to our previous report, the second-order red QW forms the defects that are the origin of an additional short-wavelength emission.\(^{26,29}\) It suggests that the SQW structure can suppress defect generation; therefore, it is well-suited for realizing a high-purity red emission and enhancing an IQE. In addition, the LEDs used a hybrid MQW structure that inserted a lower In-content blue SQW underneath a main InGaN red QW active layer.\(^{25}\) The hole-blocking n-AlGaN barrier layer between blue and red QWs was applied to suppress the hole injection into the blue QW. The InGaN active region consisted of Al(Ga)N barrier layers with open.
band engineering and strain compensation to enhance the light-output power.\textsuperscript{16,24,31} The AlN capping layer was used to prevent In evaporation during the high-temperature barrier growth step.\textsuperscript{24}

The LED devices were fabricated in a conventional face-up configuration. The 100-nm-thick indium tin oxide (ITO) films were deposited on p-layers as a transparent ohmic contact layer using e-beam evaporation.\textsuperscript{24} The LED mesas were formed by inductively coupled plasma etching. The rectangular-shaped LED chips had a mesa width of 280 $\mu$m and a length of 800 $\mu$m, with a calculated emitting area of 197 300 $\mu$m$^2$. A combination of Cr (50 nm)/Pt (195 nm)/Au (200 nm) metal structures were deposited as n- and p-pad electrodes. The LEDs were packaged with epoxy resin to enhance light extraction efficiency.

We characterized the resulting LED devices by electroluminescence (EL) under direct current (DC) operation at room temperature (RT). The light-output power of the LEDs was measured by a calibrated integrating sphere.

The LED presents the current dependence of EL measurement at RT. Figure 2(a) shows an EL emission with a peak wavelength of 621 nm and a full-width at half-maximum (FWHM) of 51 nm at a 20 mA injection current. The narrow FWHM contributes to obtaining a high-purity emission, as shown in Fig. 2(b). The FWHM emission of the LEDs is comparable to state-of-the-art InGaN-based LEDs in the red spectral range.\textsuperscript{16,18,23,33} However, we found additional emission peaks in the blue spectral range with increasing current injection, as shown in Fig. 2(c). The additional EL intensities were negligibly weak compared with the main EL emissions. We examined the EL mapping of the red LEDs at a 20 mA injection current, as shown in Fig. 2(d). The EL mapping image presented the homogeneous emission from the InGaN red SQW. Regarding our previous report, the additional emission should present point-like emissions in the vicinity of the defects.\textsuperscript{30} Thereby, the SQW active layer suppressed any unexpected additional short-wavelength emissions-related defects. In this work, we believe that the additional emission phenomenon arises from hole overflow due to less number of red QW. We found that the carrier confinement was sufficient at low current density until 10 A/cm$^2$. However, it was not enough to overcome that current density even with a high potential barrier.
structure in the InGaN red QW and a hole-blocking n-AlGaN barrier layer. Moreover, the peak emission wavelength of the LEDs displayed a large blue shift from 641 to 606 nm with injection currents ranging from 2 to 100 mA, as shown in Fig. 3(a). This large blue shift is caused by screening the internal electric field in the c-plane InGaN QWs as the injection current increases. The bandfilling of the localized state due to the In fluctuation can also be attributed to a large shift with the low current operation. Remarkably, these blue-shift phenomena occur when the In-content in InGaN QWs increases. Therefore, the InGaN red QW exhibited a large blue shift compared with the blue and green QW emissions. In contrast, the FWHMs were drastically reduced in the low current range and reached a minimum value of 51 nm at 20 mA. We suggest that the filling of localized states in the InGaN active layer became saturated as the current increased. However, the FWHMs started to increase as the injection current exceeded 20 mA due to the heat generated by the Shockley–Read–Hall (SRH) nonradiative recombination associated with defects in the InGaN active region. Increases in the device temperature should induce the filling of the high-energy localized states due to large In fluctuations in InGaN QW. The defects in the InGaN active region reduced the IQE and FWHM increases. The crystalline quality of the InGaN QW is attributed to its low-temperature growth and large lattice mismatch. Moreover, the Commission Internationale de l’Eclairage (CIE) 1931 chromaticity diagram corresponding to the EL spectra in the red emission range at injection currents ranging from 2 to 100 mA, as shown in Fig. 3(b). The InGaN-based red LEDs exhibited the CIE 1931 coordinates of \((x, y) = (0.685, 0.3121)\) at 2 mA operation, which was close to the Rec. 2020 for \((x, y) = (0.708, 0.292)\).

**FIG. 3.** (a) Current dependences of the EL peak wavelength and FWHM of the LEDs. (b) CIE 1931 color coordinates of the EL spectra at different injection currents. The star symbol is the primary red color defined in the Rec. 2020 standard.

**FIG. 4.** (a) Light-output power and forward voltage of the LEDs at different injection currents. (b) Output power density with different peak wavelengths compared with other works. The solid and open symbols correspond to conventional- and micro-LEDs, respectively.
InGaN-based red LEDs at 2 and 2.9% at 20 mA (10.1 A/cm² injection currents, as shown in Fig. 5. The EQE and WPE were 4.3% and 2.96 V at 20 mA. We obtained an output power density of 1.7 mW at 20 mA. We also calculated the EQEs and WPEs of the LEDs at various injection currents, as shown in Fig. 5. The EQE and WPE were 4.3% and 2.9% at 20 mA (10.1 A/cm²), respectively. The EQE value of InGaN-based red LEDs at ≥10 A/cm² is considered high in the red emission range at over 620 nm emission peak wavelength.

We also calculated the EQEs and WPEs of the LEDs at various injection currents, as shown in Fig. 5. The EQE and WPE were 4.3% and 2.9% at 20 mA (10.1 A/cm²), respectively. The EQE value of InGaN-based red LEDs at ≥10 A/cm² is considered high in the red emission range at over 620 nm emission peak wavelength. There are some difficulties in realizing those results. InGaN-based LEDs are difficult to obtain over 620 nm peak emission in a high current density operation due to the large blue shift. The In-content of InGaN QWs is needed to extend the emission wavelength. At this moment, the EQE should drastically drop because the SRH nonradiative recombination increases by the degradation of InGaN QW quality and the large QCSE. We believe that the EQE of InGaN-based red LEDs can be further improved by advanced growth technology.

In summary, here we describe InGaN-based LEDs in the red emission range at over 620 nm emission peak wavelength. The light-output power, forward voltage, and EQE of the 621-nm LEDs were 1.7 mW, 2.96 V, and 4.3% at 20 mA (10.1 A/cm²) injection current, respectively. The output power density of the LEDs was as high as 0.87 W/cm² at 20 mA operation. These results are promising for highly efficient red micro-LEDs.

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AUTHOR DECLARATIONS
Conflict of Interest
The authors have no conflicts to disclose.

Author Contributions
Daisuke Iida: Conceptualization (lead); Investigation (lead); Methodology (lead); Validation (lead); Writing – original draft (lead); Writing – review & editing (equal). Pavel Kirilenko: Investigation (supporting); Methodology (supporting); Validation (equal). Martin Velazquez-Rizo: Investigation (supporting); Methodology (supporting); Validation (equal); Visualization (equal). Zhuang: Investigation (supporting); Methodology (supporting); Validation (equal). Kazuhiro Ohkawa: Conceptualization (equal); Supervision (lead); Validation (equal); Writing – review & editing (equal).

DATA AVAILABILITY
The data that support the findings of this study are available within the article.

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