Phosphor-free white light-emitting diode with laterally distributed multiple quantum wells

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A phosphor-free white light-emitting diode (LED) was fabricated with laterally distributed blue and green InGaN/GaN multiple quantum wells (MQWs) grown by a selective area growth method. Photoluminescence and electroluminescence (EL) spectra of the LED showed emission peaks corresponding to the individual blue and green MQWs. The integrated EL intensity ratio of green to blue emission varied from 2.5 to 6.5 with the injection current below 300 mA, but remained constant at high injection currents above 300 mA. The stability of the emission color at high currents is attributed to parallel carrier injection into both MQWs. © 2008 American Institute of Physics [DOI: 10.1063/1.2890492]

White light-emitting diodes (LEDs) have attracted a great deal of attention for applications such as solid-state lighting and display backlight units. The conventional method to achieve white LEDs is to combine a phosphor wavelength converter with a blue or ultraviolet LED. However, the degradation of phosphor material during long-term optical pumping decreases the output efficiency of the white LEDs and a Stokes shift energy loss is unavoidable in phosphor-based white LEDs. Moreover, complex packaging steps are needed to fabricate phosphor-based white LEDs. To solve these problems, much has been reported about the development of phosphor-free white LEDs by combining two or three multiple quantum wells (MQWs). These LEDs usually consist of vertically stacked blue and green InGaN/GaN MQWs inserted between the n-GaN and p-GaN layers because of difficulties in the growth of yellow and red light-emitting InGaN/GaN MQWs. In vertically stacked LEDs, the ratio of blue to green electroluminescence (EL) often changes with injection current due to nonuniform injection of electrical carriers into the MQWs. Because the mobility of holes is lower by an order of magnitude than the mobility of electrons in GaN, the radiative recombination of electrical carriers in active layers is dominated by the hole transport. Variation in the EL intensity ratio is therefore attributed to an imbalance in the injection of electrical carriers into the MQWs connected in series. For solid-state lighting applications, color stability of white LED at high injection currents is strongly required. In this letter, we propose a white LED with laterally distributed blue and green MQWs, which has a stable color at high injection currents.

Figure 1 illustrates the schematic structure and fabrication process of a dual wavelength white LED with blue and green MQWs by using a selective area growth method. After growth of five pairs of InGaN/GaN blue MQW at 780 °C on 2 μm thick n-GaN which was grown on sapphire substrate by metal organic chemical vapor deposition, a 100 nm thick SiO2 layer was deposited by plasma-enhanced chemical vapor deposition. A SiO2 line pattern with a width of 5 μm and period of 10 μm was then fabricated by a combination of photolithography and wet etching using a buffered oxide etchant (BOE). The open area of the blue MQW layer was removed by an inductively coupled plasma (ICP) etching process using Cl2/CH2/H2/Ar as source gases until the n-GaN layer was exposed. Five pairs of green InGaN/GaN MQWs were then selectively grown on the etched area at 750 °C. As shown in the scanning electron microscope (SEM) image of the surface in Fig. 2(a), the green MQWs were grown selectively on the patterned area of blue MQWs. After the SiO2 mask was removed by BOE, the line patterns disappeared. The surface has become flat, as shown in Fig. 2(b), indicating that the blue and green MQWs have the same thickness. A 0.2 μm thick p-GaN layer was grown at 900 °C, which was 100 °C lower than the conventional

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** (Color online) A schematic of the fabrication flow of the dual wavelength white LED using laterally distributed green and blue MQWs.

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growth temperature of p-GaN to protect the green MQWs from thermal damage.\textsuperscript{11} The surface of the p-GaN layer, grown on top of the laterally distributed blue and green MQWs, did not show any line pattern, as shown in the top view image in Fig. 2(c) and side view image in inset of Fig. 2(d). An atomic force microscope image of the p-GaN layer in Fig. 2(d) also shows that the surface is atomically flat with a root mean square roughness of 4.25 nm. A few pits formed on the surface due to the low temperature growth of p-GaN.

To fabricate LEDs with a size of 300 × 300 \(\mu\)m\(^2\), the p-GaN and MQW layers were etched away by ICP until the n-GaN layer was exposed for n-type Ohmic contact formation. Ti/Al and Ni/Au layers were used for the n- and p-type electrodes, respectively.

Figure 3 shows the normalized photoluminescence (PL) spectra of individual blue and green MQWs, as well as, the laterally distributed MQWs. The emission wavelengths of the blue and green MQWs are 431 and 511 nm, respectively. The integrated PL intensity of the green emission peak is 1.7 times smaller than that of the blue peak. The low luminescence efficiency of the green MQW has been known to be due to the enhanced quantum-confined Stark effect and increase of defects in green quantum wells.\textsuperscript{12} The laterally distributed MQWs show two PL peaks centered on 433 and 513 nm. The lateral diffusion length of photogenerated carriers in InGaN heterostructures has been estimated to be a few hundred nanometers at room temperature,\textsuperscript{13} a value much smaller than the 5 \(\mu\)m width of each quantum well.

As shown in the inset of Figs. 4(a) and 4(b); however, the blue and green EL emission peaks become saturated and slowly decrease above currents of 250 mA due to Joule heating induced reduction of recombination efficiency of the InGaN based MQWs.\textsuperscript{15} As shown in the inset of Figs. 4(a) and 4(b), the blue MQW showed much smaller blue-shift than the green MQW and showed red-shift above 200 mA, indicating that the piezoelectric field in the blue MQW is fully screened by the injected carriers. Because the piezoelectric field induces spatially indirect transition in the InGaN wells,\textsuperscript{16} the indirect transition rate of electron and hole is low in the green MQWs, while spatially direct transition rate is high in the blue MQWs. This results in the decrease of the EL intensity ratio with increasing the injection current before the piezoelectric field in the green MQW is fully screened by the increased carriers. As the injection current increases from 200 to 300 mA, how-
ever, the EL intensity ratio increases from 2.5 to 4.9. This can be attributed to the lower carrier overflow in green MQWs than in blue MQWs. The blue MQWs with smaller band offsets between the InGaN well and GaN barrier layers compared to green MQWs induces weak carrier confinement, resulting in a large carrier overflow in the blue MQW at high injection current. Therefore, it is expected that the EL emission efficiency decreases much faster in the blue MQWs than in the green MQWs, resulting in the increase in the intensity ratio of green to blue EL emission. Above 300 mA, the EL intensity ratio was nearly constant as shown in Fig. 4(b). We attribute this to that almost all the localized states in both blue and green MQWs are filled and that the piezoelectric field is fully screened by increased carriers at high injection current. The ratio of carrier recombination efficiency in both MQWs is therefore nearly independent of current. This finally results in small variation of EL intensity ratio of green to blue at high injection current, as shown in Fig. 4(b). When blue and green MQWs are stacked vertically between p- and n-GaN, the emission ratio changes significantly with increasing injection current even at high injection currents.

As mentioned previously, the radiative recombination in a GaN p-n junction is mainly determined by hole transport because the mobility of holes is lower than that of electrons by an order of magnitude in GaN. Therefore, the recombination sites of the electrons and holes shift gradually from the p-type side to the n-type side in the active layer as the current increases. This effect results in large variations of emission intensity ratio of the green to blue MQWs when they are stacked vertically. However, when the blue and green MQWs are grown laterally as in our case, electrons and holes are simultaneously injected into both MQWs even though their mobilities are significantly different. This greatly reduces the variation in emission intensity ratios at high injection currents. The stable emission color at high injection current is advantageous for an application of phosphor-free white LEDs to solid-state lighting and display applications. These results indicate that growing a lateral distribution of various MQWs emitting lights with different wavelengths is a promising approach to the creation of phosphor-free white and multicolor light-emitting sources.

In summary, a phosphor-free white LED was proposed and fabricated using a laterally stacked structure of blue and green InGaN-based MQWs. The laterally stacked MQWs showed two distinct PL emission peaks at the expected wavelengths. The LED showed emission peak in blue and green spectral range simultaneously. The EL intensity ratio of green to blue emission showed very little variation at high injection currents compared to that of the reported white LED using vertically stacked MQWs because charge carriers are injected into the blue and green MQWs in parallel.

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