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Efficient emission of InGaN-based light-emitting diodes: toward orange and red

SHENGNAN ZHANG, JIANLI ZHANG,* JIANGDONG GAO, XIAOLAN WANG, CHANGDA ZHENG, MENG ZHANG, XIAOMING WU, LONGQUAN XU, JIE DING, ZHIJUE QUAN, AND FENGYI JIANG

National Institute of LED on Silicon Substrate, Nanchang University, Nanchang 330096, China
*Corresponding author: zhangjianli@ncu.edu.cn

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Indium gallium nitride (InGaN)-based light-emitting diodes (LEDs) are considered a promising candidate for red-green-blue (RGB) micro displays. Currently, the blue and green LEDs are efficient, while the red ones are inefficient for such applications. This paper reports our work of creating efficient InGaN-based orange and red LEDs on silicon(111) substrates at low current density. Based on the structure of InGaN yellow LEDs, by simply reducing the growth temperature of all the yellow quantum wells (QWs), we obtained 599 nm orange LEDs with peak wall-plug efficiency (WPE) of 18.1% at 2 A/cm^2. An optimized QW structure was proposed that changed two of the nine yellow QWs to orange ones. Compared with the sample containing nine orange QWs, the sample with two orange QWs and seven yellow QWs showed similar emission spectra but a much higher peak WPE up to 24.0% at 0.8 A/cm^2 with a wavelength of 608 nm. The improvement of peak WPE can be attributed to the improved QW quality and the reduced active recombination volume. Subsequently, a series of efficient InGaN-based orange and red LEDs was demonstrated. With further development, the InGaN-based red LEDs are believed to be attainable and can be used in micro LED displays.

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1. INTRODUCTION

Red-green-blue (RGB) micro light-emitting diode (LED) displays and related applications are attracting extensive attention in recent years because of their outstanding features [1–4]. Besides the difficulty in transferring massive LED chips to the matrix, it is also a great challenge to fabricate efficient red LED chips in micro size. Currently, most commercial red LED chips are made of normal-sized aluminium gallium indium phosphide (AlGaInP) material with efficiency above 50%. But when the chip is reduced to micro size, the efficiency drops down dramatically as it has high surface recombination due to the high minority carrier diffusion length [5–7]. Moreover, the AlGaInP material has poor mechanical properties [8], low thermal stability [9,10], and incompatible geometry if it is integrated with InGaN-based blue and green LEDs in one pixel. Fortunately, we have the InGaN material, which theoretically can emit visible light of any wavelength. Meanwhile, the InGaN material has high thermal stability, excellent mechanical and chemical properties, and does not pose harm to the environment compared with arsenide or phosphide [11,12]. More importantly, the size effect of InGaN was reported to not be as substantial as that of AlGaInP [13–15]. Thus, InGaN could be a promising material for micro red LED if the efficiency can be raised to an acceptable level.

It is known that the efficiency of InGaN-based LEDs decreases rapidly with increasing wavelength, which is probably due to the increase in indium content in the multi-quantum wells (MQWs). A QW with longer wavelength requires higher indium content and lower growth temperature, which forms more dislocations, point defects, and severe phase separation, and ultimately leads to an increase in non-radiative recombination and lower efficiency [16,17]. The blue and green InGaN-based LEDs are very efficient to date. The typical value of peak wall-plug efficiency (WPE) is ~78% for 448 nm blue at ~3.5 A/cm^2 [18] and ~56% for 534 nm green at ~1 A/cm^2 [19]. However, the WPE of InGaN-based orange or red LEDs is below 2.5% [20–26].

By improving the material quality, reducing the compressive strain of InGaN QWs, and enhancing hole injection by three-dimensional (3D) p-n junctions with V-pits, we have successfully pushed the peak WPE of 574 nm yellow LEDs to 33% at 3 A/cm^2 [27]. It is expected to have a good result if we apply the InGaN-based yellow LED technology to orange and red ones. In this paper, based on our previous work on InGaN-based yellow LEDs [27], we attempted to extend the efficient emission of InGaN QWs from yellow to orange and red; as a result, a significant advancement was made.

2. METHODS AND RESULTS

The InGaN-based orange LED films were grown on patterned silicon(111) substrates by a self-designed, metal-organic, chemical vapor deposition reactor [28]. The epi-structure was similar to that of the yellow LED reported previously [27], which consisted of a 2.8 μm n-GaN layer, 32 periods of 5 nm $In_{0.1}Ga_{0.9}N$/2 nm-GaN superlattices, nine periods of 2.5 nm $In_{0.4}Ga_{0.6}N$/13.5 nm GaN orange MQWs, a 10 nm p-$Al_{0.2}Ga_{0.8}N$ electron block layer (EBL), and a 130 nm p-GaN layer. Compared with the yellow LEDs, the only change in material growth was to reduce the growth temperature of yellow QWs from 780°C to 760°C for orange LEDs. The schematic structure is illustrated in Fig. 1(a).

To emphasize the importance of V-pit in InGaN-based LEDs, especially for long wavelength emission, a V-pit is added in the drawing of the structure. Besides the benefits of "3D p-n junction" to screen dislocations and enhance hole injection [29–33], we find that V-pits are also helpful to the growth of orange QWs. The voids of V-pits in the bulk can reduce compressive strain, which is very crucial to growing InGaN QWs with high indium content. From the aspect of obtaining high efficiency, the density and the size of V-pits must be controlled. For V-pit density, if it is too high, too many dislocations will lower the efficiency; if it is too low, the hole injection path will become too long. For V-pit size, if it is too small, it will affect the dislocation screening results; if it is too large, it will reduce the effective volume of MQWs. According to our experiments, the optimized density and average size of V-pits are 10^9 cm^{-2} and 150 nm, respectively.

Even though material growth was based on the optimized methods of yellow QWs, it was still very hard to grow high-quality InGaN orange QWs. The QW quality is not only determined by the indium content of each QW, but also by the accumulated indium amount of all the QWs. With such a high indium content and so many periods, the material quality of the active region is presumed to be worsened with the growth of more orange QWs. An optimized LED structure was proposed, as illustrated in Fig. 1(b). Instead of changing all the yellow QWs to orange ones, only two (QW7 and QW8) of the nine yellow QWs were changed to orange ones. The first six yellow QWs (QW1 to QW6) can act as a buffer to improve the crystal quality of the two orange QWs. The last yellow QW (QW9) can protect the two orange QWs from being damaged by high temperature during the subsequent p-GaN growth. The transmission electron microscope (TEM) image of the MQWs presented in Fig. 1(c) shows very abrupt interfaces, indicating good QW quality for Sample B. With the help of V-pits, the holes can flow easily into the two orange QWs because it has a narrower bandgap with lower energy potential. Thus, the dominant emission is expected to be from the two orange QWs when the current density is low [28,29,32]. Less active QWs mean less active recombination volume. Reducing the active recombination volume can help to shift the efficiency peak toward lower current density; this is consistent with the demand of micro LED applications which often work at low current densities.

The two LED samples, denoted as Sample A and Sample B, were fabricated into LED chips with a size of 1 mm × 1 mm and a roughened top surface and silver (Ag) reflector-coated backside via the reported film transferring technique [27,34,35]. A direct current power supply (Keithley 2635) and a spectrometer (Instrument Systems CAS140CT) equipped with an integrating sphere (Instrument Systems ISP250-211) were used for electroluminescence (EL) tests. A light source (Nikon Intensilight C-HGFI) was used for fluorescence luminescence (FL) tests.

Figures 2(a) and 2(b) show the room temperature EL spectra of Sample A and Sample B, respectively. It is observed that the emission spectra of the two samples are similar within a low current density range from 0.4 to 10 A/cm^2. It is inferred that the two orange QWs in Sample B are the main emission region at low current densities, and the remaining seven yellow QWs in Sample B do not contribute much to the emission, which is consistent with our expectations. Both samples have a large wavelength shift around 30 nm from 0.4 A/cm^2 to 10 A/cm^2, which is much larger than that of yellow (∼15 nm), green (∼10 nm), and blue (∼3 nm) LEDs, indicating stronger quantum confinement Stark effects (QCSE) in orange QWs.

The WPE of the two samples at different current densities is plotted in Fig. 3(a). For Sample A, it has a peak WPE of 18.1% at 2 A/cm^2 with a wavelength of 599 nm. Though the result is a record for an InGaN-based orange LED, it still does not meet

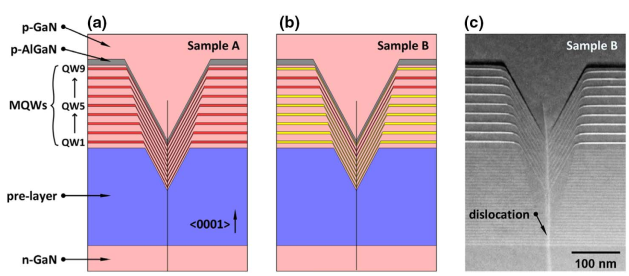

Fig. 1. Schematic epi-structures of InGaN-based orange LEDs on silicon(111) substrates: (a) Sample A with nine orange QWs and (b) Sample B with two orange QWs and seven yellow QWs. (c) TEM image of a cross section near the active region of Sample B. For easier presentation, the full thicknesses of n-GaN and p-GaN are not shown.

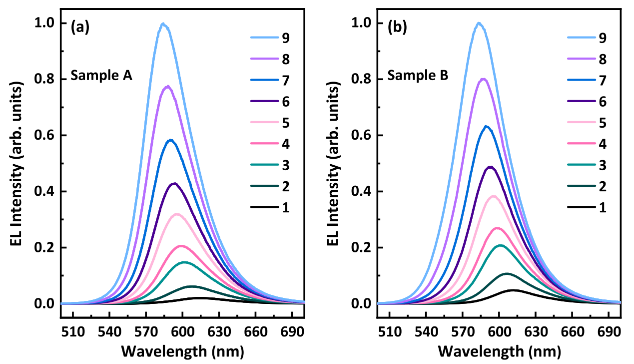

Fig. 2. Room temperature electroluminescence spectra of (a) Sample A and (b) Sample B, where lines 1 to 9 correspond to a current density of 0.4, 0.8, 1.5, 2.0, 3.0, 4.0, 5.5, 7.5, and 10.0 A/cm^2, respectively.

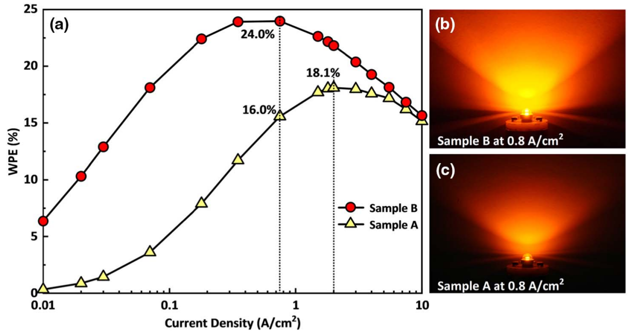

Fig. 3. (a) Room temperature dependence of WPE on the current density of InGaN-based orange LEDs on silicon(111) substrates. Emission photos of (b) Sample B and (c) Sample A driven at a current density of 0.8 A/cm^2.

our expectation if we compare it with the peak WPE of the yellow LED in Ref. [27] (33% @ 2 A/cm^2, 574 nm) and in our recent work (42.8% @ 1 A/cm^2, 577 nm) [36]. The dramatic reduction of peak WPE can be mainly attributed to the deterioration of QW quality as a result of increased indium content in the orange QWs.

With a reduced number of orange QWs, Sample B has a much higher efficiency than Sample A, especially at low current densities. The peak WPE of Sample A is increased to 24.0%, where the current density is 0.8 A/cm^2 and the wavelength is 608 nm. Compared with the WPE of Sample A (16.0%) at the same current density and with the same wavelength of 608 nm, a 50% improvement is made for Sample B. The luminescence images of the two samples driven at 0.8 A/cm^2 are presented in Figs. 3(b) and 3(c). One can find that Sample B is much brighter.

Generally, an increase in peak efficiency means an improvement in the quality of the QWs [37]. When comparing the FL images, Sample A shows a non-uniform red emission with many dark regions in Fig. 4(a), while Sample B shows a much more uniform red emission in Fig. 4(b). Such dark spots presented in FL images are often due to the phase separation of the In-content in MQWs of InGaN-based LEDs [19,24,38,39]. Thus, the results suggest that the high In-content phase separation problem in the orange QWs has been suppressed by reducing the number of orange QWs in Sample B, and the quality of the orange QWs has been greatly improved.

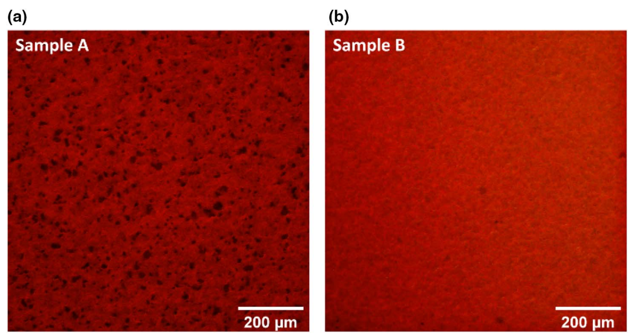

Fig. 4. Fluorescence luminescence images of InGaN-based orange LEDs on silicon(111) substrates, (a) Sample A and (b) Sample B, under an excited lamp source with a wavelength range from 510 to 560 nm.

The efficiency depends closely on the carrier recombination which is influenced by a change in the structure [40]. It is known that the energy gap of an orange QW is narrower than that of a yellow QW. With the help of V-pits for hole injection, most carrier recombination is believed to have occurred in the orange QWs at low current densities, and the active recombination volume is reduced in Sample B. It is known that current and active recombination volume can be expressed as follows:

$$j = q \int (R_{\mathrm{RAD}} + R_{\mathrm{NR}}) \mathrm{d}V / S_E, \tag{1}$$

where j is the current density, q is the elementary charge, V is the active recombination volume, S_E is the current injected area, R_{RAD} is the radiative recombination rate, and R_{NR} is the non-radiative recombination rate. As a result, for Sample B, the radiative recombination rate in the orange QWs can be greatly enhanced due to the suppressed non-radiative recombination caused by the quality improvement of the orange QWs and the decrease in active recombination volume (when the driven current density is the same). Therefore, the WPE of Sample B is much higher than that of Sample A at low current densities.

Adopting the structure of Sample B, a series of InGaN-based LEDs with various wavelengths ranging from orange to red were successfully developed on silicon(111) substrates. All the samples have the same structure as Sample B, and the only change was to adjust the growth temperature of QW7 and QW8.

The dependence of room temperature EL properties including WPE, full width at half-maximum (FWHM) of the emission spectrum, and the voltage on the peak wavelength are plotted in Fig. 5. All the devices are measured at 0.8 A/cm^2. The WPE of the InGaN-based LEDs is 30.1% at 594 nm and drops down to 16.8% at 621 nm, which

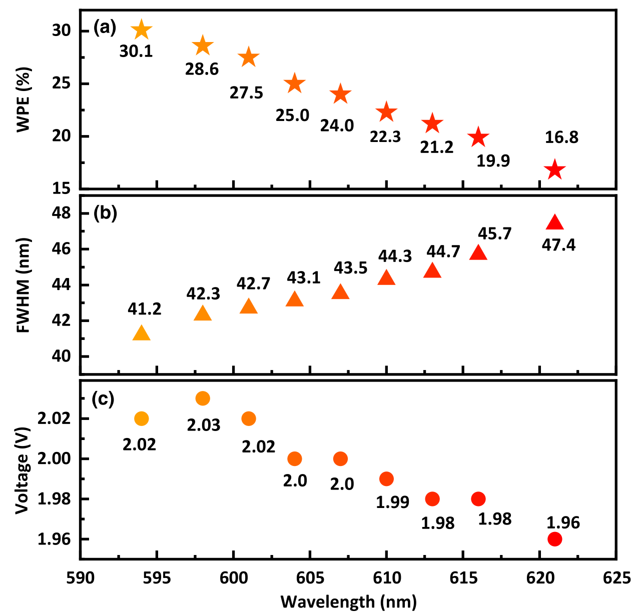

Fig. 5. Dependence of (a) WPE, (b) FWHM, and (c) voltage on the peak wavelength of InGaN-based orange and red LEDs at room temperature and at a current density of 0.8 A/cm^2.

has a similar trend and decreasing slope compared with that of yellow LEDs [26]. The FWHM increases from 41.2 to 47.4 nm as the peak wavelength increases from 594 to 621 nm, which is a bit large for a micro display. Further optimization might be able to reduce it to less than 40 nm. The voltage has a negative relationship with wavelength, where the values are 2.02 V at 594 nm and 1.96 V at 621 nm. It is interesting to note that the voltage drop is lower than the average energy of emitted photons for all the samples; the extra energy is probably coming from the thermal energy carried by the carriers.

It should be pointed out that the LED chips in this paper are of normal size (1 mm × 1 mm), which is much larger than that of micro LEDs. Our micro LED chip technology is still under development.

3. CONCLUSIONS

In conclusion, we conducted research on InGaN-based orange and red LEDs based upon the structure of InGaN-based yellow LEDs. Instead of changing all the yellow QWs to orange ones, we proposed an optimized QW structure that only changes two of the nine yellow QWs to orange ones. The LED with the optimized structure was found to be much more efficient, and it achieved a record high WPE of 24.0% with a peak wavelength of 608 nm at 0.8 A/cm^2. The enhanced efficiency is attributed to the improved quality of the orange QWs and the decreased active recombination volume. Based on the optimized QW structure, a series of efficient InGaN-based orange and red LEDs, with peak wavelengths from 594 nm to 621 nm and corresponding WPE from 30.1% to 16.8% at 0.8 A/cm^2, were successfully developed. The results show that the material quality of InGaN-based red LEDs is very close to meeting the demands of micro display. With the development of micro LED chip technology and a further improvement in material growth, it is believed that InGaN-based red LEDs for micro display are feasible in the near future.

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